Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California

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Movement and Sediment Yield of Two Earthflows, Northwestern California

By K.M. NOLAN *and* R.J. JANDA

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

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454-F

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By K.M. NOLAN and R.J. JANDA

ABSTRACT

Movement rates as high as 15.3 meters per year and annual sediment yields as high as 25,100 megagrams per square kilometer have been measured at two earthflows in the Redwood Creek basin of northwestern California. More than 90 percent of the sediment delivered from the earthflows to adjacent streams was delivered by earthflow movement between 1977 and 1982. Less than 10 percent of the sediment measured leaving the earthflows was delivered by fluvial processes operating in earthflow-gully systems. Movement rates and colluvial sediment yields depend upon both the amount and the pattern of seasonal precipitation, as well as the constantly changing mass distribution within individual earthflows. Annual moisture conditions appear to control the timing of movement, and the distribution of mass within the earthflow appears to control temporal and spatial variations in the rate at which movement occurs. Transient mass distributions make extrapolation of the collected data through time difficult. Although the data may only partially characterize the full range of movement rates and sediment yields possible from the studied earthflows, the complex relationship between factors responsible for controlling the behavior of these and similar earthflows has been illustrated.

INTRODUCTION

Many hillslopes in the rapidly eroding Coast Ranges of northwestern California are dominated by large complex earthflows. Although earthflows are obvious sources of sediment that affects instream and near-stream resources, quantification of the sediment yield derived from these persistently active features requires long-term observation. This report characterizes movement and sediment yield from two earthflows, primarily from 1977 to 1982, by presenting information from repetitive surveys of transverse and longitudinal lines of stakes and from borehole inclinometer measurements, recording strain gages, recording rain gages, and records of water and sediment yield from gully systems developed on the surfaces of the studied earthflows.

Study sites 2 and 3 (fig. 1), representing the two earthflows studied in this report, are part of a larger network of sites in the Redwood Creek basin of northwestern California at which surficial movement rates have been monitored. Description of this larger network is in Harden and others (1978).

DESCRIPTION OF EARTHFLOWS

The two earthflows studied are complex associations of sheared and fractured earth debris, in elongate or lobate masses, that move downslope relatively slowly along boundary shear zones. At least some parts of these masses move annually. This persistent movement produces depressions in the landscape that are manifested as hummocky ground, scarps, tension cracks, and compressional ridges. The morphology and mechanics of similar earthflows have been described by Varnes (1958), Prior and others (1971), Colman (1973), Swanson and James (1975), Keefer (1977), Kelsey (1978), and others. Ten percent of the Redwood Creek basin is covered by earthflows (Nolan and others, 1976).

The earthflows studied, like most others in the Coast Ranges of northern California, are developed on rapidly eroding hillslopes underlain by rocks of the Franciscan assemblage of late Jurassic and Cretaceous age (Harden and others, 1981). This assemblage consists predominantly of sandstones and mudstones in association with significant amounts of metamorphosed volcanic rocks, serpentinite, chert, and limestone (Bailey and others, 1964; Jones and others, 1978). The sandstones and mudstones often are highly fractured and sheared. Earthflow development, as well as regional sediment yields that are among the highest in North America (Judson and Ritter, 1964; Janda and Nolan, 1979), results from these structurally weak rock units in combination with steep hillslopes and abundant wintertime precipitation.

A Mediterranean climate prevails at both study sites. Average annual precipitation, 80 percent of which typi-

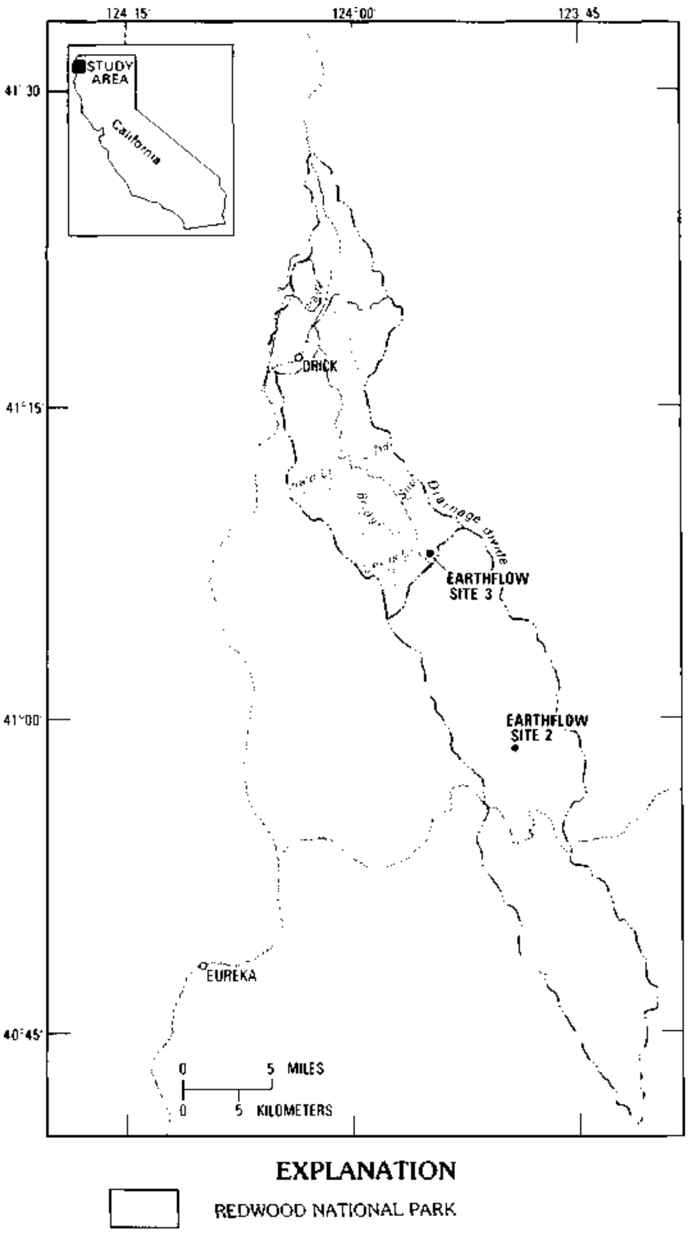

FIGURE 1.—Location of sites 2 and 3 in the Redwood Creek drainage basin.

FIGURE 2.—Location of sampling and measurement sites on earthflow at study site 2. Aerial photograph taken July 14, 1979.

cally falls between October and April, is approximately 2,000 mm at both study sites.

DESCRIPTION OF SITE 2

Site 2 is adjacent to the main channel of Minor Creek (figs. 1, 2). This site displays morphological features characteristic of many earthflows in Franciscan terrane but lacks the typical teardrop shape. The upper one-third of site 2 is dominated by a large upper slump block and a prominent crown scarp. Data from inclinometer tubes indicate that movement at depth occurs below this upper slump block, within a basal shear zone. Observations of compressional ridges, lateral shear zones, hummocky ground, scarps, and tensional cracks indicate that movement above this shear zone involves a complex

FIGURE 3.—Toe of earthflow at study site 2. Photograph taken March 1980. Note effects of undercutting by main channel of Minor Creek and large colluvial blocks that result from persistent movement of toe. Note top of 6-in. flume and gage-height recorder for scale.

assemblage of regions, each characterized by slumping, flowing, and (or) translational sliding. Similar observations were made by Keefer (1977) and Kelsey (1978). The toe of site 2 is dominated by translational sliding and small surficial slumps and slides (fig. 3). The active portion of site 2 is 760 m long and averages 150 m wide. Relief is about 230 m.

The lower two-thirds of site 2 contains several prominent longitudinal gullies that coalesce into two well-defined channels at the earthflow toe and that transport sediment directly into Minor Creek. Vegetation on the earthflow surface is mostly grass and some brush and small oaks. Bare soil is exposed at the head scarp, in gully walls, on a translational slide at the earthflow toe, and where a county road crosses upper portions of the earthflow. The ground is dry during late spring and summer, except in a small area of ponded drainage near transverse stake line 2 and near the base of the earthflow toe, where small amounts of seepage are evident.

DESCRIPTION OF SITE 3

Site 3 is on the east side of Redwood Creek (figs. 1, 4) and is underlain by sandstone and mudstone that are closely fractured and sheared near the earthflow toe but relatively massive in the crown area. Site 3 displays the typical teardrop shape absent in site 2. Movement in the crown area is dominated by slumping or sliding of relatively coherent blocks. Material moving through the relatively narrow midslope portions is highly disrupted

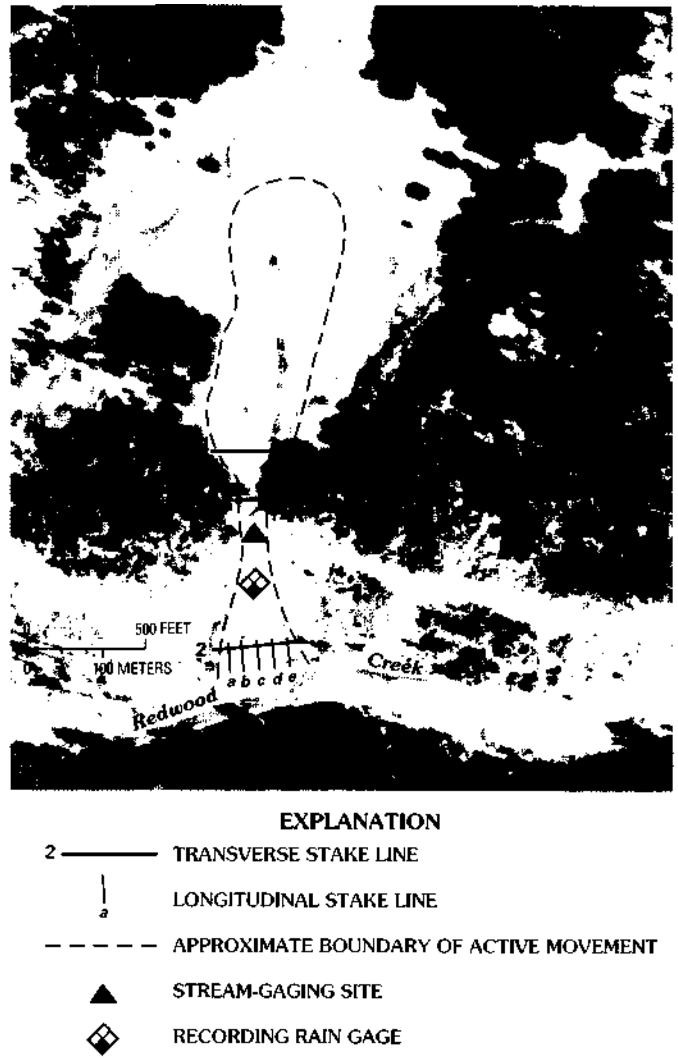

FIGURE 4.—Location of sampling and measurement sites on earthflow at study site 3. Aerial photograph taken July 14, 1979.

and appears to move by a combination of flow and translational movement. The earthflow toe is dominated by a large translational slide, the surface of which is covered by small shallow slides and slumps. Drainage is poorly defined on the upper two-thirds of the earthflow but merges into a single well-defined axial gully in the lower one-third. The active portion of site 3 is 340 m long and 140 m wide and has 110 m of relief.

Vegetation on the earthflow is mostly grass and bracken fern and some brush, small oaks, and conifers. The ground surface is commonly severely disrupted by extension cracks 15 to 30 cm deep, by lateral shear surfaces, and by compressional ridges (fig. 5). Stands of tilted oaks and young conifers are present at the lateral edges of the flow. The ground surface is generally dry in the late spring and summer.

FIGURE 5.—Hummocky ground near transverse stake line 1, site 3.

SURFICIAL MOVEMENT OF EARTHFLOWS

TRANSVERSE STAKE LINES

Surficial movement rates were monitored from the 1974 water year to the 1982 water year[1] at site 2 by repetitive surveys of five transverse lines of stakes and from the 1975 water year to the 1982 water year at site 3 by surveys of three transverse lines of stakes. Stakes were spaced at 4.5-m intervals across each feature, and stake positions were surveyed by theodolite at least annually from stable instrument locations at the end of each line. The horizontal component of stake displacement was calculated from the horizontal angle between the location of individual stakes and the line between the two stable end points. Stake line locations are shown in figures 2 and 4, and survey results are summarized in tables 1 and 2 by showing average and maximum stake movement for each water year.

LOCATION OF STAKES AT SITE 2

Transverse stake line 1 on site 2 transects the earthflow directly below its crown scarp and uphill from an area of compressional ridges. Line 2 is located at the narrowest part of the flow, where the edges of the lateral scarps defining the active portion of the feature are 3 to 6 m higher than the flow surface. Stake line 3 crosses the flow where a less active, tributary earthflow enters the main feature. At stake line 4, the earthflow is wider and less steep than at the upper portions. Stake line 5 transects the flow about 30 m upslope from the streamside edge. Portions of line 5 transect the toe translational slide.

LOCATION OF STAKES AT SITE 3

Transverse stake line 1 on site 3 is located immediately above the area indicated by field reconnaissance to be the most active portion of the feature. Line 1A is located at the narrowest portion of the feature where field evidence suggested that movement rates would be the highest. The lower line, line 2, crosses the flow at a gently sloping hummocky area immediately above the toe translational slide.

LONGITUDINAL STAKE LINES

Five lines of longitudinal stakes were placed at the toe of site 2 in the 1977 water year and at the toe of site 3 in the 1978 water year. These lines were installed to better monitor movement of colluvial debris into adjacent streams. Stake movement was determined from triangulation surveys using stable instrument locations near the earthflow toes. Stake line locations are shown in figures 2 and 4, and surveying results are summarized in tables 1 and 2.

MOVEMENT PATTERNS OF EARTHFLOWS

Although slow earthflow movement appears to persist throughout the water year on some regions of site 2, movement generally resumes or accelerates in the late autumn or early winter following the start of the rainy season and the resulting increases in soil moisture and pore-water pressure. The patterns of movement observed in this study illustrate the importance of cumulative moisture on earthflow movement. The movement pattern recorded during the 1979 water year at the two strain gages near the toe of site 2 (fig. 2), as illustrated in figure 6, is typical of patterns monitored at all strain gages between 1978 and 1981. Even though brief periods of intense precipitation occurred early in the 1979 water year, movement was not initiated until antecedent moisture conditions were high. Once movement began, it accelerated quickly and continued despite the lack of prolonged periods of intense precipitation. Moisture conditions optimal for maximum movement probably occur when prolonged periods of rainfall occur early in the rainy season. Sufficient moisture to initiate some degree of rapid movement occurred during all years of study. Monthly and annual precipitation recorded at each site is shown in table 3.

[1] Water year extends from October 1 to September 30.

TABLE 1.—*Surficial movement rates (horizontal component) at site 2*

[Average (Avg) refers to average movement of all stakes on line. Maximum (Max) refers to maximum individual stake movement. Locations of stake lines are shown in figures 2 and 4. All measurements are in meters. —, no data]

	Transverse stakes										Longitudinal stakes				
	Line 1		Line 2		Line 3		Line 4		Line 5		Line a	Line b	Line c	Line d	Line e
	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Avg	Avg	Avg	Avg
Stakes per line	37		26		48		49		23		9	9	7	6	9
Total length	130.1		84.7		190.5		174.2		116.1		22.7	23.4	14.3	12.1	19.6
Water year:															
1974	---	---	0.86	1.52	0.56	1.94	0.23	1.55	---	---	---	---	---	---	---
1975	0.09	0.17	.06	.1	.13	.27	.05	.26	0.16	0.55	---	---	---	---	---
1976	.17	.38	.08	.14	.01	.1	[1]	[1]	.33	.84	---	---	---	---	---
1977	.03	.07	.03	.12	.04	.1	10	.26	.04	.15	0.23	0.12	0.09	0.02	0.18
1978	.6	.87	.10	.23	.08	.13	[2].04	.15	.58	.63	3.78	3.32	.57	.16	.2
1979	.22	.31	.07	.15	.07	.11	[2].06	.15	.39	2.41	1.38	3.39	.65	1.53	.56
1980	.42	.62	.23	.51	.19	.31	.06	.24	2.48	15.30	5.98	10.25	.64	1.13	.43
1981	.17	.26	.07	.17	.09	.15	.05	.10	1.32	6.43	3.07	5.13	.61	.19	.08
1982	.5	.82	.36	.54	.20	.47	.31	1.22	1.81	15.29	4.60	6.67	15.36	.76	.79

[1] End point destroyed during 1976 water year and reestablished.
[2] Includes only movement on left one-half of line.

TABLE 2.—*Surficial movement rates (horizontal component) at site 3*

[Average (Avg) refers to average movement of all stakes on line. Maximum (Max) refers to maximum individual stake movement. Locations of stake lines are shown in figures 2 and 4. All measurements are in meters. —, no data]

	Transverse stakes						Longitudinal stakes				
	Line 1		Line 1A		Line 2		Line a	Line b	Line c	Line d	Line e
	Avg	Max	Avg	Max	Avg	Max	Avg	Avg	Avg	Avg	Avg
Stakes per line	21		13		18		13	14	15	13	14
Total length	58.2		54.2		39.0		33.4	34.9	34.1	27.7	28.9
Water year:											
1975	0.03	0.08	_	_	0.21	0.63	_	_	—	_	_
1976	.01	.12	_	_	.15	.54	_	_	_	_	_
1977	.00	.04	_	_	.07	.32	_	_	_	_	_
1978	.05	.25	_	—	.52	1.92	2.79	2.24	1.38	_	.58
1979	.11	.45	0.02	0.11	.65	2.34	2.17	4.11	.78	[1]1.48	.54
1980	.03	.18	.02	.12	.30	1.08	1.04	1.67	.75	.78	2.26
1981	.03	.10	.04	.10	.04	.15	.22	.34	.09	.05	.00
1982	.10	.36	.30	1.64	.45	1.90	2.74	3.08	.85	.61	2.71

1 Includes 1978 and 1979 movement.

TABLE 3.—*Monthly and annual precipitation measured at sites 2 and 3*

[All measurements are in millimeters; —, no data]

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Yearly total
Site 2									
1974	- - - - - No recording data - - -								[1]3,030
1975.	60	150	371	404	439	646	120	47	2,255
1976.	359	234	183	150	381	136	61	11	1,598
1977.	26	94	10	39	126	203	46	91	746
1978.	124	356	445	242	184	186	173	61	1,908
1979.	3	126	60	266	339	79	132	142	1,205
1980.	—	[2]681	51	308	273	257	112	92	2,160
1981.	83	163	269	199	177	231	40	66	1,260
1982.	220	472	591	291	456	419	195	—	2,721
Site 3									
1975.	.........No recording data. . .								2,259
1976.	337	290	225	144	400	150	82	18	1,730
1977.	21	97	20	133	141	177	4	96	850
1978.	157	426	425	383	270	167	189	8	2,270
1979.	1	147	54	246	406	75	169	132	1,297
1980.	391	184	291	349	306	318	147	54	2,044
1980…..	79	165	330	255	224	252	44	89	1,466
1982.	.................No recording data.........................								2,360

[1] Based on correlation with record collected at Prairie Creek Redwoods State Park (U.S. National Oceanic and Atmospheric Administration, 1973–74).
[2] October total added to November total.

In addition to the general relations found between annual moisture conditions and earthflow movement, the individual characteristics of each feature must be considered. Because earthflows consist of distinct units, patterns of movement may vary at different locations within the same feature. This variation in movement behavior is illustrated in figures 7 and 8, which show for study sites 2 and 3, respectively, the cumulative movement of a single stake at each of the transverse stake lines. Stakes chosen for these figures were all located within the active portion of the line. Although there is some similarity in the timing of relative movement at individual stake lines, there also are a number of inconsistencies. For example, the stake on line 5, site 2, showed maximum movement during the 1980 water year, but movement at line 4 during that year was only slightly faster than that for 1979 or 1981. Similarly, maximum movement on line 1, site 2, was recorded during the 1978 water year, while movement rates for lines 2 and 3 for that year were some of the slowest recorded.

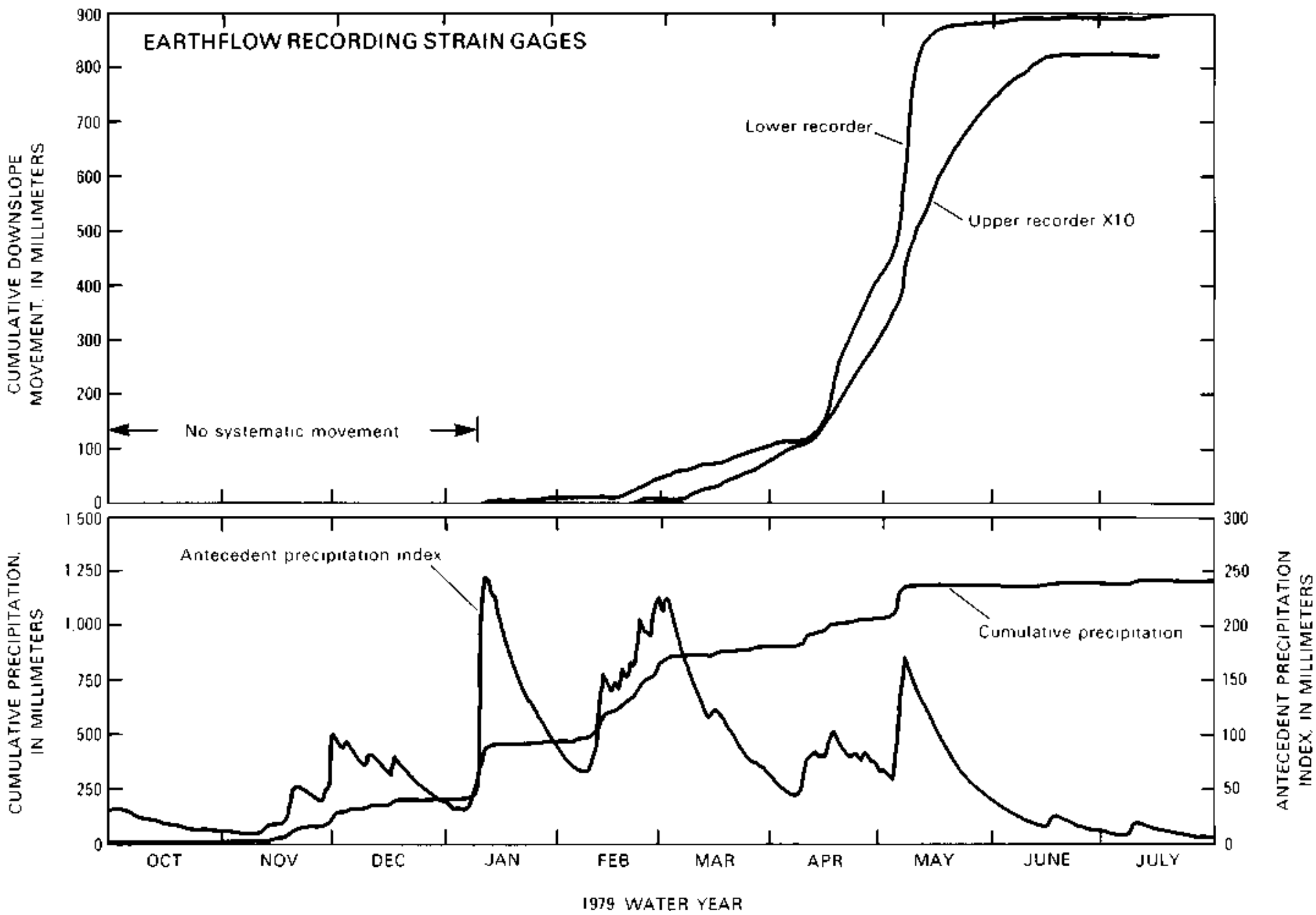

FIGURE 6.—Earthflow movement at site 2 recorded at strain gages during the 1979 water year. Cumulative precipitation is from daily rainfall measured at site. Antecedent precipitation index was determined by using a daily decay constant of 0.94 (Linsley and others, 1949). Lower recorder is at upslope end of longitudinal stake line *b* on traverse line 5 (fig. 2). Upper recorder is 50 m upslope of lower recorder.

Field observations indicate that this irregular earthflow behavior is caused by the constantly changing mass distribution within individual features. The distinct units within earthflows are characterized by different rates and styles of movement, and the movement of any one unit may affect movement of adjacent units. Individual units commonly are bounded by distinct lateral margins, and the fastest movement usually occurs near the center of each unit. The movement pattern recorded at transverse stake line 2, site 3, is illustrated in figure 9.

Movement, at least at earthflow toes, also appears to be controlled by the action of the stream channels adjacent to the toes. The anomalously high movement rates during 1980 at line 5, site 2 (fig. 7), resulted from undercutting of the toe by the main channel of Minor Creek (fig. 3). Conversely, alluvium deposited by the main channel of Redwood Creek appears to have effectively buttressed the toe of site 3 and caused anomalously low movement rates at line 2 during 1980 and 1981 (fig. 8).

MOVEMENT OF EARTHFLOWS AT DEPTH

INCLINOMETER TUBES

In cooperation with the U.S. Forest Service, six inclinometer tubes were installed near transverse stake line 3, site 2, beginning in the 1979 water year (fig. 2). Repetitive measurements in these tubes indicate a distinct basal shear zone at an average depth of 4.9 m. Apparent deformation at inclinometer tube E is shown in figure 10, and the estimated location of the basal shear zone below the inclinometer tube sites is shown in figure 11. Tube D showed no apparent shear zone due to its limited depth (4.42 m) and high relative elevation.

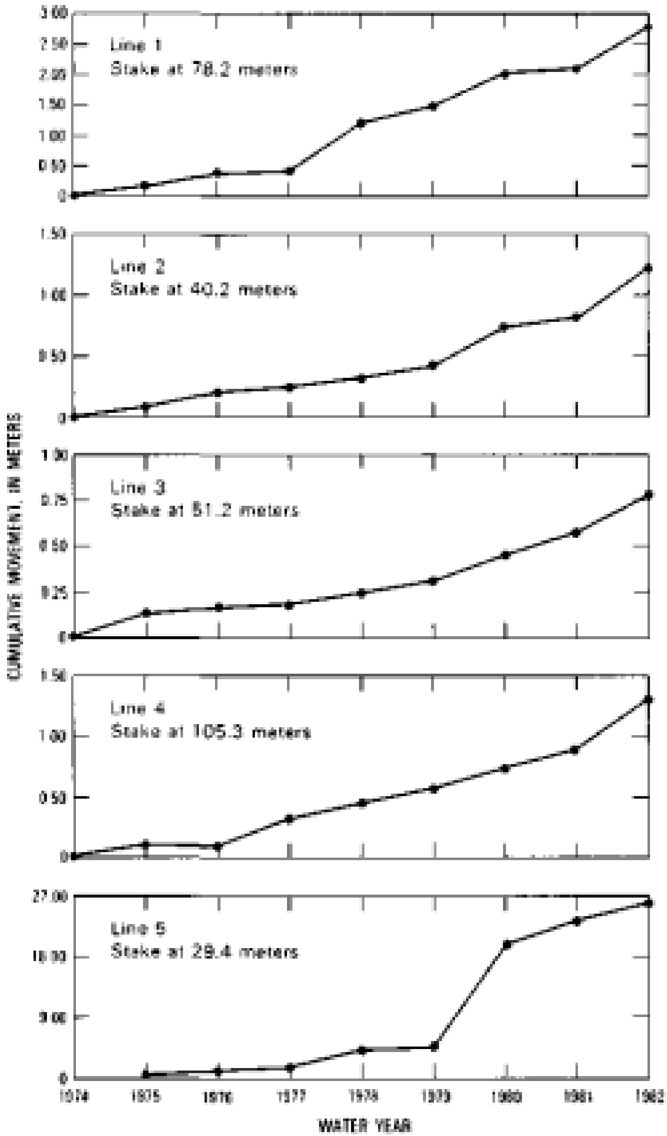

FIGURE 7.—Cumulative movement of selected transverse stakes at site 2. Movement rates are indicated by slope of lines connecting data points. Note variation in movement scale (x-axis). Stake distances are measured from left side of lines as viewed from looking downhill.

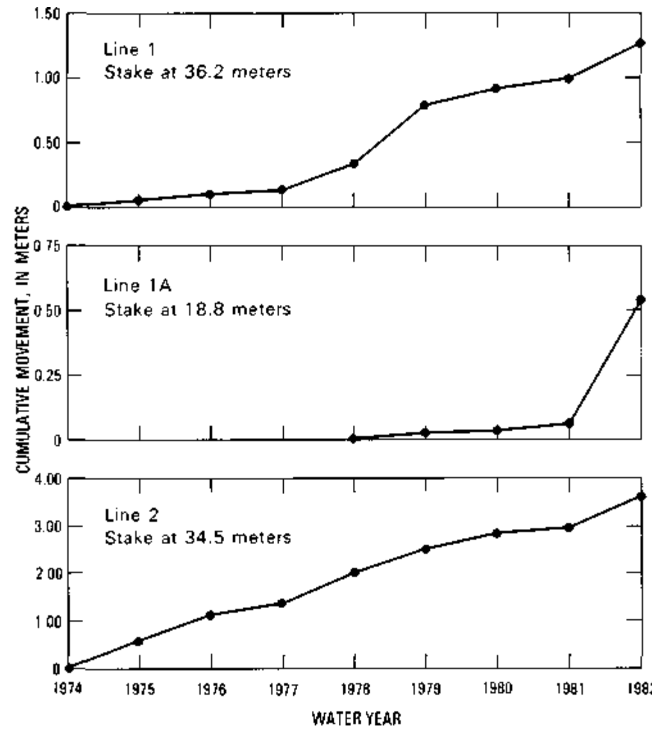

FIGURE 8.—Cumulative movement of selected transverse stakes at site 3. Movement rates are indicated by slope of lines connecting data points. Note variation in movement scale (y-axis). Stake distances are measured from left side of line.

DEPTHS OF MOVEMENT AT EARTHFLOW TOES

The steep, actively eroding nature of the earthflow toes precluded installation of inclinometer tubes at these sites. Since repeated field observations indicated that mass movement at the earthflow toes did not disrupt the adjacent channel bottoms, movement was assumed to extend from the surface downward to a concave-upward basal shear zone between the base of the streambanks and the heads of toe translational slide.

Movement at these sites appears to persist at an almost uniform rate throughout the year. This relatively slow movement contrasts with that of the more rapid, highly seasonal movement seen along at least some portions of most stake lines and at the toe strain gages, site 2. Because the shear zone remains saturated all year long (Richard Iverson, U.S. Geological Survey, oral commun., 1983), this slow movement may reflect movement along this zone under relatively low pore-water pressures. The more rapid seasonal movement may result from the localized increases in pore-water pressures that occur during rainy periods.

SEDIMENT YIELDS FROM EARTHFLOWS

COLLUVIUM

Colluvial yield to adjacent stream channels was calculated from hillslope geometry, movement rates determined during surveys of longitudinal stake lines, and estimated movement depths. The total annual volume of material delivered to adjacent stream channels by mass movement was calculated by using average movement at each of the five longitudinal lines, slope width between each stake line, and estimated depth to the basal shear zone. The cross-sectional geometry used to calculate the volume of colluvium delivered at longitudinal line e in the

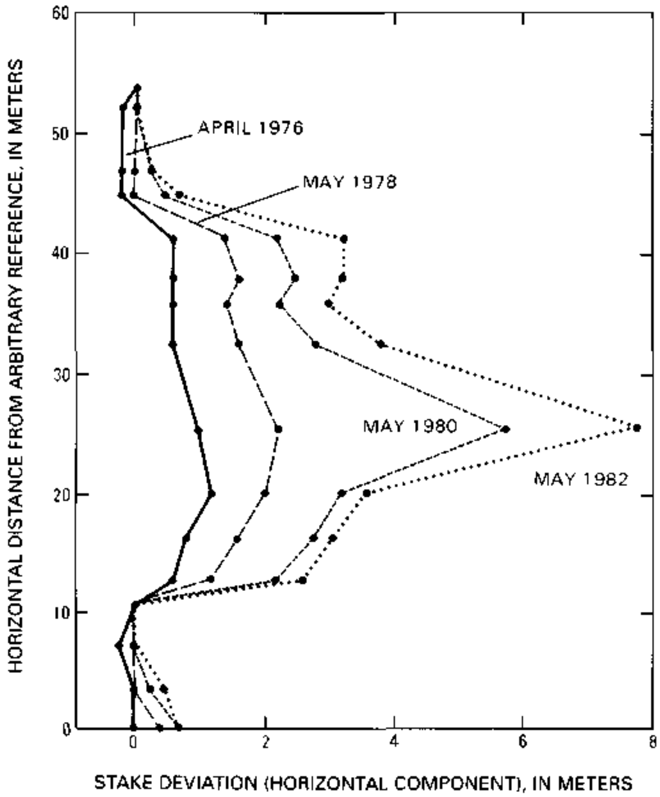

FIGURE 9.—Downslope displacement of stakes at transverse stake line 2, site 3. Only stakes not lost or replaced during period of record are shown to better depict continuous movement. Numbers indicate the number of stakes plotted at that location.

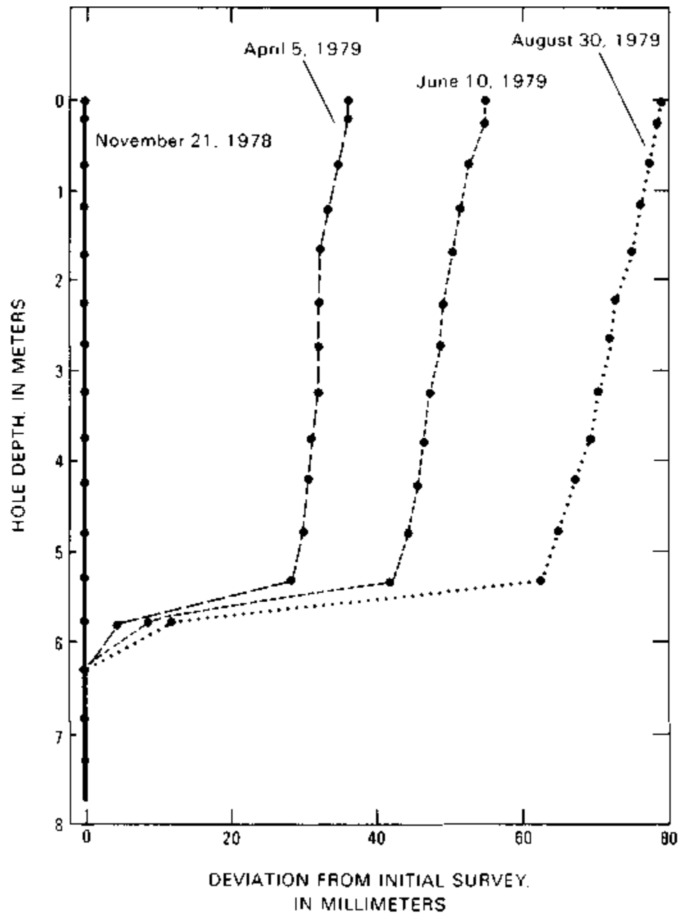

FIGURE 10.—Apparent deformation at inclinometer tube E, site 2. Deformation in tube after August 30, 1979, was too severe to allow penetration by inclinometer. Hole depth was 7.85 m. Data are from R. Ziemer, U.S. Forest Service, Arcata, Calif.

1981 water year is illustrated in figure 12. Annual volume estimates were converted to annual sediment yields by applying an average density of 2.08 g/cm^3 (grams per cubic centimeter). Annual colluvial sediment yields determined for both study sites are shown in tables 4 and 5. The colluvium was delivered directly to active stream channels adjacent to the toes of both earthflows. The area where colluvium was deposited was generally inundated on an annual basis, and most colluvium was removed frequently. The rate at which colluvium was removed varied somewhat and depended upon the location of the channel thalweg during individual years.

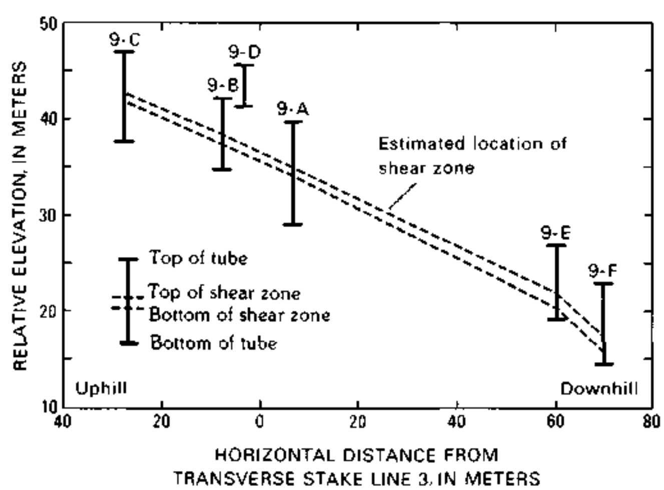

FIGURE 11.—Estimated location of basal shear zone beneath inclinometer tube locations. Inclinometer tubes were installed near transverse line 3, site 2.

FLUVIAL SEDIMENT

The highly disrupted material of earthflows is extremely vulnerable to gully erosion, and both sites 2 and 3 are drained by gully systems. For this reason, continuous water-level recorders, located at either weirs or flumes, were installed in 1978 at major gullies draining sites 2 and 3. Total annual sediment yield was determined for each site by using gage-height records and

TABLE 4.—*Sediment discharge by mass movement, fluvial erosion, and runoff at toe of site 2 and amount of material move transverse stake line 3 (midslope portion), site 2*

[Drainage area is 0.13 km . —, no data]

Water year	Sediment discharge						Runoff		
		Suspended sediment		Bedload					
	Mass movement (Mg)	Right gully (Mg)	Left gully (Mg)	Right gully (Mg)	Left gully (Mg)	Total sediment discharge (Mg/km²)	Right gully (m)	Left gully (m)	Movement past stake line 3 (m)
1977	1.50	---	---	---	---	[1]12	---	---	32.3
1978	372.3	—	—	—	---	[1]2,850	—	---	64.6
1979	305.8	[2]125.0	[2]0.50	[2]31.2	[2]0.1	3,550	0.29	0.43	56.6
1980	2,806	112.5	19.1	28.1	4.8	22,800	.85	.96	153.6
1981	705.1	20.1	2.2	5.0	.6	5,650	.41	.52	72.7
1982	3,132	97.6	4.5	26.9	1.1	25,100	1.59	1.75	161.6

[1] Does not include fluvial discharge.
[2] Record starts December 15, 1978.

TABLE 5.—*Sediment discharge by mass movement, fluvial erosion, and runoff at toe of site 3*

[Drainage area is 0.023 km². —, no data]

Water year	Sediment Discharge			Total sediment (Mg/km²)	Runoff (m)
	Mass movement (Mg)	Suspended sediment (Mg)	Bedload (Mg)		
1978	230.5	—	—	[1] 10, 020	—
1979	466.3	2.0	0.5	20,380	1.19
1980	155.2	[2]12.4	[2]25.1	8,380	[2]1.86
1981	3.3	8.5	5.0	730	1.27
1982	376.9	([3])	([3])	16,380	([3])

[1] Does not include fluvial discharge.
[2] Record starts December 13, 1979.
[3] Measuring site destroyed by debris slide.

periodic measurements of water, bedload discharge, and suspended-sediment concentrations. Sampling was concentrated during rainy periods. Two stream-gaging sites were established at site 2 and one at site 3 (figs. 2, 4). Bedload at site 3 was trapped behind an enlarged weir structure beginning in the 1979 water year. Bedload discharges for site 3 in 1978 and for site 2 were estimated by using the median value of the percentage of total load that bedload represented at times of instantaneous measurement of suspended-sediment and bedload discharge. This procedure was necessary due to the lack of significant relationship between water discharge and bedload discharge. Water discharge and suspended-sediment discharge were determined by using standard U.S. Geological Survey field and office techniques (Buchanan and Somers, 1969; Porterfield, 1972). Sampling-site locations are shown in figures 2 and 4, and sampling results are shown in tables 4 and 5.

The amount of seasonal runoff measured at site 3 was consistently high, relative to seasonal rainfall measured at the site. The surface beneath this and similar features is likely to be severely disrupted, and the high runoff percentages may reflect effects of a phreatic drainage divide that differs from the mapped topographic divides.

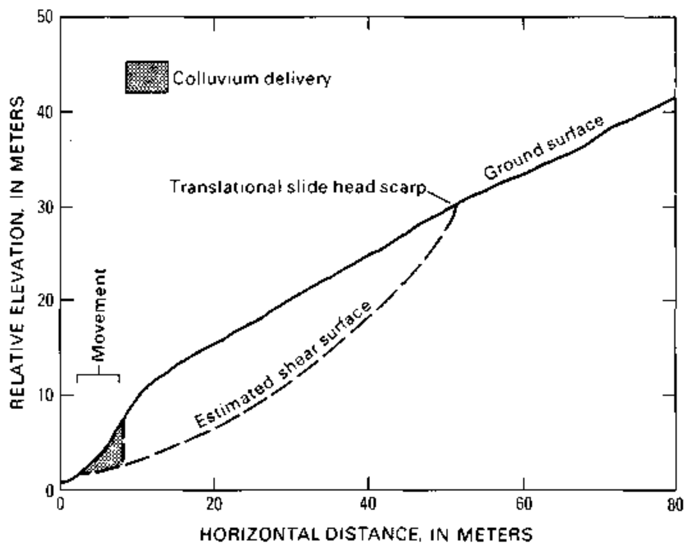

FIGURE 12.—Geometry used to estimate sediment delivery at toe of site 2, longitudinal stake line *e*.

DISCUSSION

TOTAL SEDIMENT YIELD

Total annual sediment yields from earthflow study sites 2 and 3 ranged from 730 to 25,100 Mg/km² (megagrams per square kilometer) (tables 4, 5). These values are from 1.6 to 18.3 times the basin wide average sediment yield, which is represented by the yield measured at Redwood Creek at Orick for similar years (table 6). The vast majority of sediment delivered from both sites to adjacent stream channels was delivered by mass movement processes. Although fluvial processes operating in major gully systems delivered up to 80 percent of the annual yield during individual years, such high percentages occurred only during years of minimal colluvial input (tables 4, 5). Ninety-three percent of the yield from site 2 between 1979 and 1982 and 92 percent of

TABLE 6.—*Total sediment discharge measured at the mouth of Redwood Creek*

[Data were gathered from stream-gaging station at Orick (no. 11482500)] [Mg/km^2, megagram per square kilometer]

Water year	Sediment discharge (Mg/km^2)	Water year	Sediment discharge (Mg/km)
1977	31	1980	1,243
1978	1,610	1981	455
1979	435	1982	Not available

TABLE 7.—*Maximum annual movement recorded at earthflows in California and Oregon*

Location	Reference	Year	Maximum movement (m)
Davailla hill .... (southwestern Oregon)	Reefer (1977)	1975	3.8
Halloween earthflow .... (northwestern California)	Kelsey (1978)	1974	21.0
Do	....do....	1975	29.0
Do	....do....	1976	28.7
Lookout Creek earthflow ..... (west-central California)	Swanson and others (1979)	1975	.10
		1976	.14
		1977	.01
		1978	.06
		1979	.13

the yield from site 3 between 1979 and 1981 were delivered by mass-movement processes (tables 4, 5).

REGIONAL COMPARISON

Surficial-movement rates monitored at sites 2 and 3 are intermediate among those measured during the same time interval at other earthflows in the Pacific Northwest. Maximum annual movement rates recorded by Kelsey (1978), Keefer (1977), and Swanson and others (1979) are compared in table 7. Data in this table indicate that earthflow movement rates, from a regional perspective, are highly variable. Although much of this variability no doubt results from variations in local moisture conditions, original ground slope, and existing mass distributions, differences in geologic setting are probably primarily responsible for the variations in rates. The rapidly moving earthflows studied by Kelsey (1978) were developed in pervasively sheared rocks of the melange unit of the Franciscan assemblage. The extremely high rates of movement at these sites may reflect the intensity of this shearing. The earthflows mentioned by Keefer (1977) were very shallow seated flows, about 1 m deep, developed in fractured shales and sandstones of the Franciscan assemblage. Movement rates at the forested Lookout Creek earthflow studied by Swanson and others (1979) were much slower than those in Franciscan assemblage terrane; this reference probably reflects the more coherent nature of the underlying volcaniclastic rocks.

Data from the sites mentioned above indicate that the sediment yields from these features also vary widely. Kelsey (1978) estimated long-term annual sediment yields at 51,200 Mg/km^2 from the exceptionally active earthflows in the Van Duzen River basin, northwestern, California, while Swanson and Swanston (1977) estimated long-term annual yield from the Lookout Creek earthflow in southeastern Oregon at 1,700 Mg/km^2 or (assuming the bulk density of the colluvium is 2.08 g/cm^3) 3,540 Mg/km^2. Estimated yield from the Van Duzen earthflows is therefore about 14 times that of the Lookout Creek feature and approximately twice the highest annual yield recorded at sites 2 or 3 of this study.

In addition to wide regional variation in sediment yields, there also appears to be wide variation in the mechanisms delivering sediment to stream channels. Kelsey (1978) estimated that fluvial processes operating in earthflow gullies annually produced approximately 26,300 Mg/km^2, whereas the highest fluvial yield recorded at sites 2 or 3 between 1978 and 1981 was 1,875 Mg/km^2. This contrast in delivery apparently results from differences in the respective sediment-transport relations or in the degree of gully-system development. Gully systems at sites 2 and 3 of this study are only moderately incised into the earthflow surface and are not integrated throughout each entire earthflow. A large percentage of the flow in gullies at sites 2 and 3 resulted from seepage of water into the gullies between rainy periods. This return flow was characterized by relatively low sediment concentrations. Gully systems on the larger features studied by Kelsey (1978) may have been better developed and, therefore, may have transported higher percentages of flow during storm periods; that is, gullies on larger features may be more actively eroding and thus may be responsible for the transport of larger percentages of total sediment discharge.

LONG-TERM SEDIMENT YIELD

Because fluvial sediment constitutes a relatively small percentage of total long-term sediment yield from sites 2 and 3, sediment yield from these features primarily reflects highly variable surficial movement rates at earthflow toes. These movement rates, and the related sediment yields, are highly variable due to factors discussed previously, and this variability is illustrated by the contrast in colluvial sediment yields from sites 2 and 3 as shown in tables 4 and 5. The yield from site 3 was higher than that from site 2 during 1978 and 1979, but the yield from site 2 was considerably higher than that from site 3 during 1980, 1981, and 1982. This change in behavior apparently resulted from the undercutting of the toe of site 2 in 1980 by Minor Creek and the buttressing of the toe of site 3 by alluvium during 1980, as discussed earlier.

Extrapolation of data collected at sites 2 or 3 in space or time appears difficult. This difficulty arises because annual sediment yields are highly dependent upon the constantly changing mass distribution existing within individual earthflows; therefore, annual sediment yields cannot be completely related to easily measured variables such as annual moisture conditions. The similar maximum recorded yields of 25,100 and 20,380 (Mg/km^2)/yr from sites 2 and 3, respectively (tables 4, 5), may indicate that these figures represent maximum yields to be expected from such features and that annual yields can be expected to range from several hundred to approximately 20,000 Mg/km^2. There are, however, indications that sediment yields greater than those recorded to date may be possible from sites 2 and 3.

Instability may be increasing on lower parts of site 2, and rates in the near future could be higher than those recorded to date. This possibility is indicated by data collected at transverse stake line 3 and at the nearby inclinometer tubes. The volume of material moving past stake line 3 has been estimated by using depth to the basal shear zone, as indicated by inclinometer tube measurements, and the earthflow width and average movement measured at stake line 3. The results of these calculations are shown in table 4. The greatest uncertainty in these calculations is the uniformity of depth to the basal shear zone. Recent data collected at additional inclinometer tube locations (Richard Iverson, U.S. Geological Survey, oral commun., 1983) tend to confirm the depth to the shear zone and to substantiate the validity of the mass flux calculations. These calculations indicate that a greater volume of material is presently passing through the toe of site 2 than is being resupplied from upper regions. Although no data are available on density variations at depth, the volume calculations indicate that a substantial mass imbalance is developing between stake line 3 and the earthflow toe, thus increasing instability. The effect of this instability on movement rates and sediment yields is uncertain. Increasing instability may lead to collapse of lower parts of the earthflow and to consequently higher movement rates and sediment yields. The nature of the developing mass imbalance is illustrated in figure 13.

Similarly, there are signs that sediment yields greater than those yet recorded may be possible from site 3. The morphology of portions of site 3 near transverse stake line 1A indicates that movement rates greater than those measured between 1975 and 1981 had persisted for some time prior to monitoring. Prominent tension cracks, lateral shear zones, and longitudinal ridges that existed in 1975 were gradually eroded and overgrown by vegetation between 1975 and 1981. Movement rates during this period did not exceed 0.12 m/yr. Movement rates at stake line 1A increased markedly in 1982 to a maximum

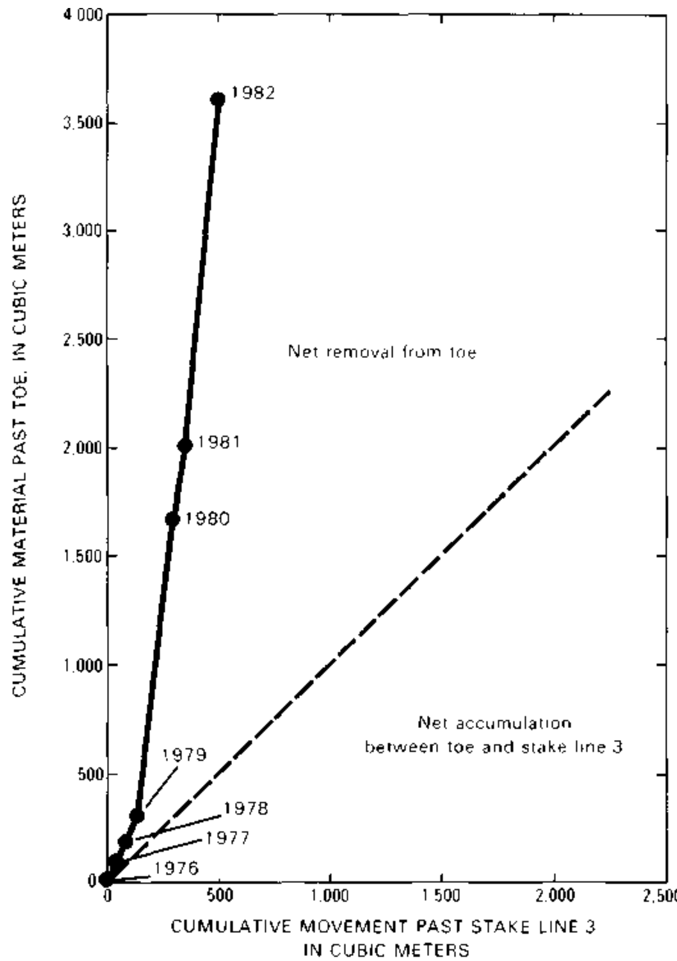

FIGURE 13.—Mass imbalance developing on lower portions of site 2 plotted as cumulative volume of material moved past stake line 3, site 2, versus cumulative volume of material moved past toe of site 2.

of 1.04 m/yr; this increase indicates a possible return to conditions sufficient to cause the features observed in 1975. Although the effects of more rapid movement at this location on movement at the toe are uncertain, persistence of the higher rates would probably lead to overloading of the toe and higher toe movement rates.

CONCLUSIONS

Data collected at study sites 2 and 3 indicate that earthflows are significant sources of sediment having annual sediment yields as much as 18.3 times the basin-wide average. Recorded annual yields between 1977 and 1982 ranged from 730 to 25,100 Mg/km^2. Although fluvial processes in gullies on the earthflows delivered up to 80 percent of the sediment during individual years, more than 90 percent of the total sediment delivered between 1979 and 1982 was delivered to adjacent streams by mass-movement processes.

Data from sites 2 and 3, as well as data collected by other workers at earthflows in nearby areas, indicate that earthflow movement rates and sediment yields are highly variable in both space and time. Movement rates and colluvial sediment yields appear to depend upon rock type and upon the constantly changing mass distribution within individual features. From a regional perspective, maximum movement rates and sediment yields are at sites that are the wettest and that are underlain by the most incoherent rocks. Within individual earthflows, maximum movement rates appear to occur when mass imbalances have exceeded stability thresholds. Annual moisture conditions control earthflow movement primarily by influencing the timing of movement and the fluvial sediment yields.

Because of the effects of underlying geology and the complex interaction between mass distribution and annual moisture conditions, extrapolation of movement rates and sediment discharge data as determined at sites 2 and 3 is uncertain, both for other earthflows and for sites 2 and 3 over time. Extrapolation to other features requires consideration of the comparability of underlying geology, climate, or potential effects of constantly changing mass distributions.

The erratic behavior of earthflows at sites 2 and 3 has resulted from a complex relationship between annual moisture conditions and transient mass distributions. Even though absolute rates of movement or sediment yield may differ, the same factors that control movement at these earthflows will control movement at other persistently active earthflows having similar morphology and failure mechanisms.

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