Flood Surge on the Rubicon River, California—Hydrology, Hydraulics and Boulder Transport

GEOLOGICAL SURVEY PROFESSIONAL PAPER 422-M

Prepared in cooperation with the California Department of Water Resources

U.S. DEPARTMENT OF THE INTERIOR

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By KEVIN M. SCOTT *and* GEORGE C. GRAVLEE, Jr.

PHYSIOGRAPHIC AND HYDRAULIC STUDIES OF RIVERS

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CONTENTS

ILLUSTRATIONS

TABLES

SYMBOLS

A	Cross-sectional area of channel	R	Hydraulic radius
a_ϕ	Phi skewness	S	Slope of water-surface gradient
D_1,D_3	Quartile size	SK_I	Inclusive graphic skewness
d	Depth of channel	S_0	Trask sorting coefficient
K	Conveyance	γ	Specific weight
M_Z	Graphic mean diameter	σ_I	Inclusive graphic standard deviation
N	Size	σ_ϕ	Phi or graphic standard deviation
n	Manning roughness coefficient	τ	Shear stress
Q	Discharge	ϕ	$-\text{Log}_2 N$

FLOOD SURGE ON THE RUBICON RIVER, CALIFORNIA—HYDROLOGY, HYDRAULICS, AND BOULDER TRANSPORT

By KEVIN M. SCOTT and GEORGE C. GRAVLEE, JR.

ABSTRACT

The failure of the partly completed Hell Hole Dam December 23, 1964, released a surge with discharge greatly in excess of any recorded flow on the upper part of the Rubicon River, a westward-drainage of the Sierra Nevada. Extensive erosion of glacial-outwash terraces along the steep, bedrock course of the stream indicates that the surge was probably greater than any post-Pleistocene discharge. Such a unique event, during which more than 700,000 cubic yards of rockfill from the breached dam embankment was washed downstream, permits documentation of the sedimentologic and geomorphic effects of a single catastrophic flow.

A torrential rainfall, 22 inches in the basin upstream from the damsite during the 5 days preceding the failure, produced dramatic and unprecedented runoff. Natural peak discharges in the region were generally equivalent to the maximum discharges attained in previous floods for which there is record. The surge release, however, produced peak discharges substantially in excess of previously recorded flows along the entire 61-mile route downstream from the damsite, along the Rubicon, Middle Fork American, and North Fork American Rivers. The discharge was still 3.3 times the magnitude of the 100-year flood on the Middle Fork American River, 36 miles downstream from the damsite. Average velocity of the flood wave was approximately 22 feet per second. Erosion of detritus from steep, thickly mantled canyon walls resulted in thalweg aggradation at five cross-profile sites. Stripping of the lower valley side-slopes may have triggered a period of increased mass movement in the gorge of the Rubicon River.

Depositional forms and flow dynamics were strongly influenced by sediment sources that included colluvium, terrace remnants, till, and landslides directly triggered by the surge. Terracelike boulder berms, probably associated with macroturbulent transport of boulders in suspension, formed in backwater areas in the uppermost Rubicon River canyon. Boulders were piled to a depth of 5 feet on a terrace 28 feet above the thalweg at a peak stage of 45 feet. Boulder fronts as much as 7 feet high that formed lobate scarps transverse to the channel in an expanding reach indicate that locally bed material moved as viscous subaqueous rockflows. Movement of coarse detritus in large gravel waves may also have occurred.

The diorite rockfill in the dam embankment acted as a point source of boulders distinguishable downstream, analogous to a natural point source of coarse particles, and allowed determination of downstream changes in sedimentological parameters. Roundness changes were rapid owing to the extreme coarseness of the material. Transition from angular to subangular occurred almost immediately after initiation of movement, and change from subrounded to rounded took place within approximately 1.5 miles of transport from the damsite. Pronounced downstream decrease in mean particle size was mainly due to progressive sorting. The effects of abrasion and breakage were relatively minor and caused less than 10 percent of the overall size decline in the section of channel from 0.4 to 1.3 miles below the damsite. Sorting improved irregularly downstream with respect to the damfill components.

Competency of the flow was approximated by a method in which tractive force is determined indirectly at the deepest point in a cross section. Tractive force was then plotted against the mean diameter of the 10 largest boulders deposited at each point where observations were made to extend the relation between tractive force and particle size into the range of extremely coarse detritus. Competency generally decreased downstream but fluctuated greatly. Great quantities of coarse material were swept laterally into the channel by the surge, but were carried only short distances downstream, as shown by variation in competence, marked decrease in size of boulders of upstream lithologic types downstream from a geologic contact, and by distance of transport of material from the dam embankment. Maximum distance of transport of any identifiable particle from the damsite was 2.1 miles.

Assessing the effects of the surge passage in terms of a natural geomorphic event, catastrophic floods, possibly resulting from landslide or ice damming as well as from unusual runoff, may strongly influence the morphology of mountain streams yet be relatively unimportant in terms of total sediment transport. Such rare floods may set the modify pool-riffle patterns, cause cycles of increased mass movement, and trigger mass flow of coarse detritus in the channel. They may cause extensive lateral supply of extremely coarse sediment to the channel where, however, the material is dispersed by flows of lesser magnitude in combination with the size-reduction effects of weathering in place.

INTRODUCTION

On December 23, 1964, impoundment of runoff from an intense and prolonged storm caused the failure of a partly completed rockfill dam on the western slope of the Sierra Nevada. A surge was released which traveled down the Rubicon River into the Middle Fork American River and into North Fork American River before final containment in Folsom Lake. Emphasis in this study is on the hydraulics of the surge flow, the movement of bed material, the resulting depositional forms, and erosional and other geomorphic effects—in short, the events following release of the surge at the Hell Hole damsite.

A description of the precipitation intensity and distribution of the storm that caused the failure, synthesis of hydrographs at the damsite based on available flow and storage records in the basin, and a description of the failure of the rockfill are included to give as full a documentation of the event as possible. What happened both before and after release of the flood wave is of interest from the standpoint of dam planning and construction on the many rivers of the West with precipitous, rock-walled canyons and steep gradients. Progressive downstream breaching of dams could effect considerable destruction, whether caused by catastrophic natural floods or possible wartime action.

The passage of the flood wave also furnished the opportunity to study the effects of an unusual hydrologic event and the role of such extraordinary floods in determining stream morphology, sedimentation, and landscape evolution. Although such after-the-fact studies of floods are necessarily limited in scope to largely qualitative observations, several aspects of this event are noteworthy. The surge on the Rubicon River was greatly in excess of any recorded natural flood discharge throughout its entire course and may have been the largest post-Pleistocene discharge to traverse the upper reaches of the Rubicon River canyon. The distinctive lithology of the rockfill from the partly completed dam provided a tracer for study of bed-material movement and changes in sedimentological parameters resulting from particle movement from a point source by a single large flow.

ACKNOWLEDGMENTS

J. C. Brice, Washington University, St. Louis, Mo., accompanied the senior writer on a preliminary reconnaissance trip into the Rubicon River canyon and made several helpful suggestions as to the conduct of the study. G. O. Balding, U.S. Geological Survey, provided valuable field assistance during most of the 18 days of fieldwork during August and September 1965.

The writers are also grateful to McCreary-Koretsky Engineers, supervisors of the construction of Hell Hole Dam, for providing reservoir-stage readings and estimates of the volume of rock washed from the breached embankment. The cooperation of I. L. Van Patten, assistant resident engineer at Hell Hole damsite, greatly expedited the fieldwork. W. A. Scott, sheriff-coroner of Placer County, provided a log of officers' observations of the downstream passage of the surge. Unpublished precipitation data were supplied by the Sacramento Municipal Utility District. Moore and Taber, Inc., permitted use of seismic measurements of one of the largest landslides triggered by the surge in the Rubicon River canyon.

The manuscript benefited from criticism by J. C. Brice, Washington University; R. K. Fahnestock, University of Texas; and George Porterfield and S. E. Rantz of the Geological Survey.

The study was part of a cooperative program with the California Department of Water Resources.

PHYSICAL SETTING

LOCATION AND PHYSICAL FEATURES

The Rubicon and American Rivers drain a part of the western flank of the Sierra Nevada in Placer and El Dorado Counties, Calif. (fig. 1), at about the latitude of Lake Tahoe. The Rubicon rises northeast of Pyramid Peak in El Dorado County at an elevation of 8,700 feet above mean sea level and flows through a broad glaciated valley before reaching the meadow known as Hell Hole, which was the site of dam construction and release of the flood wave. Hell Hole is 65 airline miles northeast of Sacramento. The surge traversed 61.1 channel miles, descended 3,800 feet (fig. 2), and finally debouched into Folsom Lake, a reservoir 20 miles northeast of Sacramento.

During its downstream movement, the flood wave passed initially through the upper glaciated part of the Rubicon River canyon, which has a length of 7.0 miles as measured from the damsite (elev. 4,250 ft) to the lowest probable Pleistocene ice terminus (3,650 ft) and an average slope of 86 feet per mile. This section of the canyon has an average width of about 2 miles and a depth of approximately 1,800 feet below the undulating, dissected erosion surface that forms the gently west-sloping flank of the Sierra Nevada. Downstream from the glaciated reaches, the flow entered the gorge of the Rubicon, a steep-walled V-shaped incision 22.7 miles in length, as much as 2,400 feet deep, and commonly less than 2 miles wide. The channel descends at a rate of 110 feet per mile between canyon walls having slopes greater than 90 percent.

Both relief and valley side-slope diminish rapidly downstream from the junction of the Rubicon with the Middle Fork American River. Several bedrock meanders of large amplitude and small radius are immediately below the junction. Canyon depth in this part of the flood route diminishes from 2,200 to 800 feet in a distance of 26.5 channel miles, and the channel slope averages 23 feet per mile. The last channel entered by the surge was the North Fork American River which slopes 19 feet per mile in the final 5.0-mile passage into Folsom Lake.

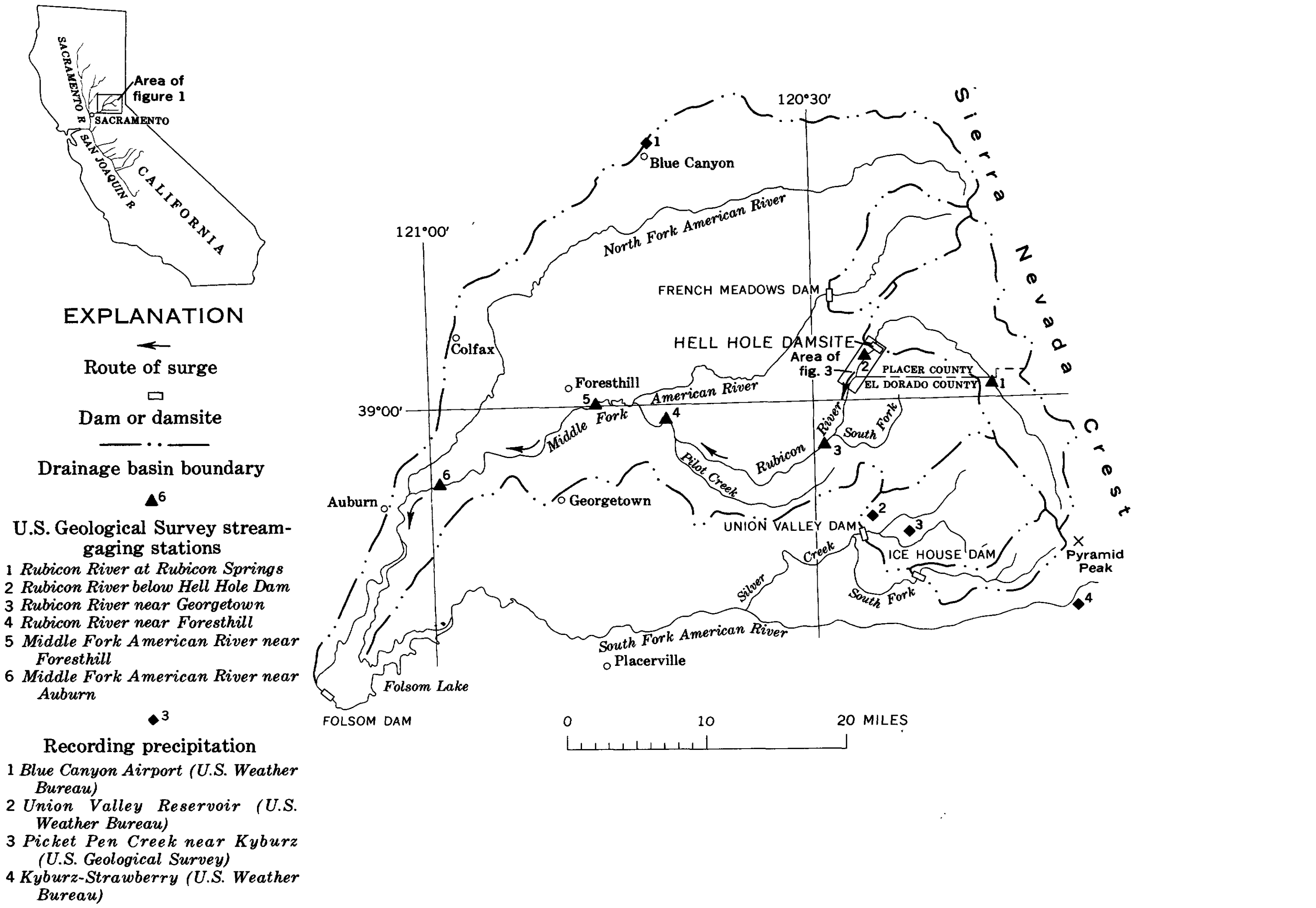


FIGURE 1.—Drainage areas in study area.

CLIMATE AND VEGETATION

Because of strong relief, the local climatic variations of the western Sierra Nevada are great, but some generalizations are possible. The area is characterized by a pattern of summer drought, punctuated by thunderstorms, and winter rain related to changes in the general circulation caused by migrating Pacific Ocean pressure centers. Rapid increase in precipitation with elevation results from rising and cooling of moist airmasses having prevailing west-to-east movement as they reach the great Sierra Nevada barrier.

Mean annual precipitation ranges from about 25 inches in the vicinity of Folsom Lake to about 60 inches at Hell Hole. The difference in precipitation total reflects orographic effects in the region. Although there is a general relation between precipitation and elevation, the orientation and exposure of an area with respect to the direction of air movement likewise affect the quantity of precipitation received, and consequently, departures from the general precipitation-elevation relation are common. Most of the total annual precipitation occurs during the period November through March. Above an elevation of 5,000 feet the precipitation is usually in the form of snow, most of which is stored in mountain snowpacks. Consequently, annual peak discharges for streams draining the higher elevations generally occur in late spring during melting of the snowpack. The peak discharges of late spring usually are not excessively large. The severe floods that infrequently occur do so during heavy winter storms when meteorologic conditions are such that the freezing level is 8,000 feet or higher, with the result that rain rather than snow occurs over most of the mountainous terrain. The catastrophic flood of December 1964 occurred under such conditions.

The vegetation pattern is highly irregular owing to strong relief and associated microclimatic changes. The canyon bottom traversed by the surge is in the Arid

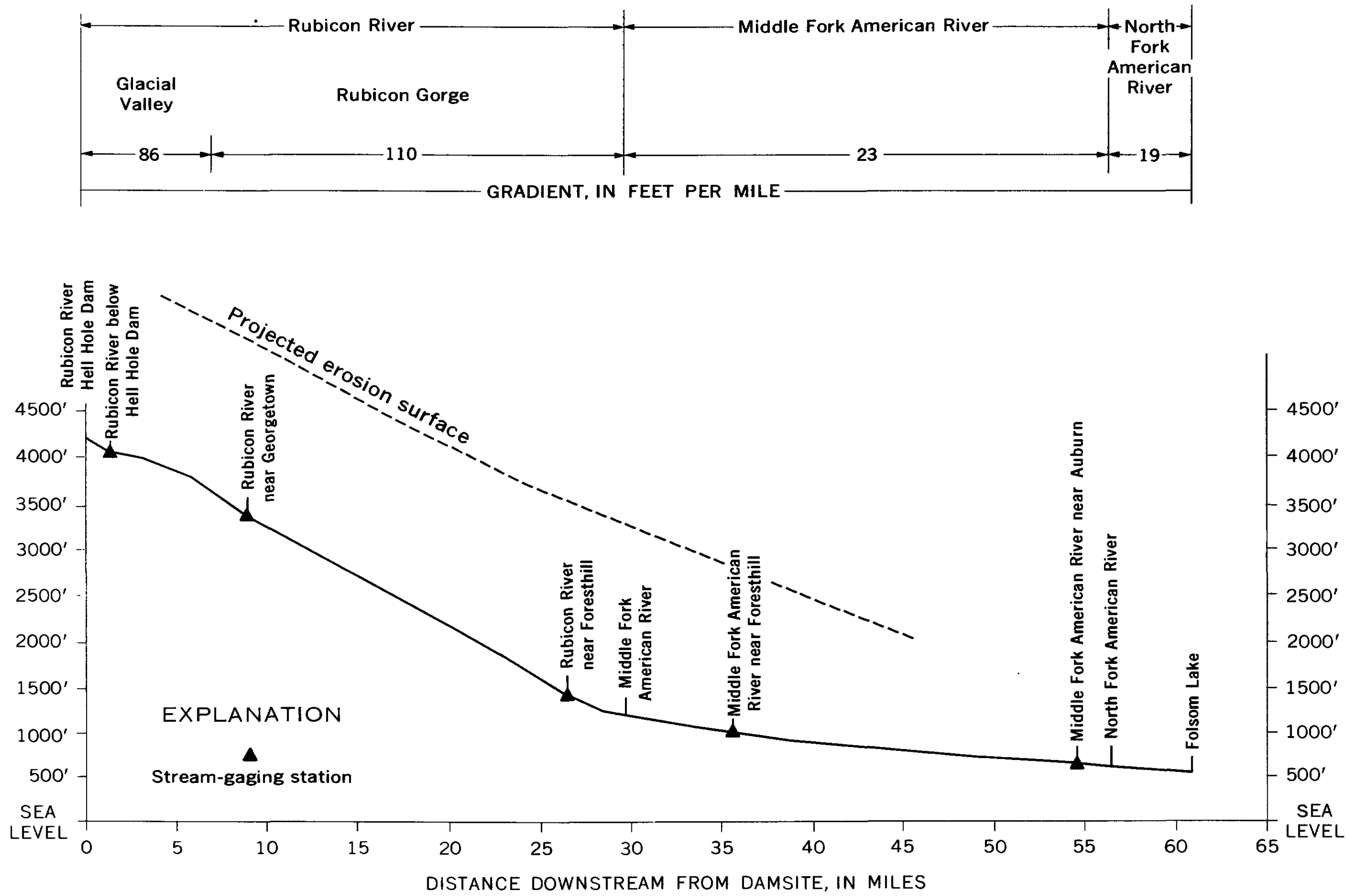


FIGURE 2.—Longitudinal profile of the flood route.

Transition life zone above an elevation of about 3,000 feet, which is substantially lower than the regional Sonoran Transition boundary because down-canyon drainage of colder air admits intrusion of higher elevation vegetation into the lower life zone. A striking difference in vegetation between opposing canyon walls was noted and is a function of isolation differences. The southerly shaded side of the canyon supports a much larger percentage of high-elevation flora.

BEDROCK GEOLOGY

Bedrock exposed in the immediate vicinity of the damsite and along the first 6 miles of channel downstream from the dam is part of a typical sierran hybrid diorite pluton. The texture of the rock is variable but generally is fairly coarse and devoid of phenocrysts. Local phases of granodiorite, gabbro, and diabase were observed. Within the reach that extends 4 miles from the damsite to the south end of Parsley Bar (fig. 3), a general increase in the quantity of mafic minerals and the number of mafic inclusions occurs. Downstream, the pluton becomes more gneissic and passes gradationally into a small roof pendant of gneiss and sericite schist, probably part of the Calaveras Formation of late Paleozoic age that forms the bedrock floor of the channel for approximately 100 yards 2.5 miles below the damsite. Downstream from the pendant, the rock is a biotite quartz diorite. Platy flow structure, schlieren, and alined mafic inclusions and segregations are present throughout the plutonic mass.

All the material used in the dam was excavated from the spillway immediately adjacent to the damsite and is a uniform massive fine- to medium-grained light-gray diorite. It is possible to differentiate the fresh hackly pieces of fill diorite washed downstream at the time of failure from the rock types naturally present as clasts in the channel. The clasts are normal dioritic alluvial boulders, substantially better rounded than the dam material, and have a white weathering patina. Angular blocks of bedrock which are derived from valley sides can be differentiated by the presence of iron-stained sheared surfaces locally crossed by dikelets.

Downstream from the junction with the South Fork Rubicon River (fig. 1), the channel is cut mainly in schist, slate, and metasandstone of the Calaveras Formation. Below the confluence of the Rubicon River with the Middle Fork American River, the channel is incised into highly sheared metasedimentary rock of

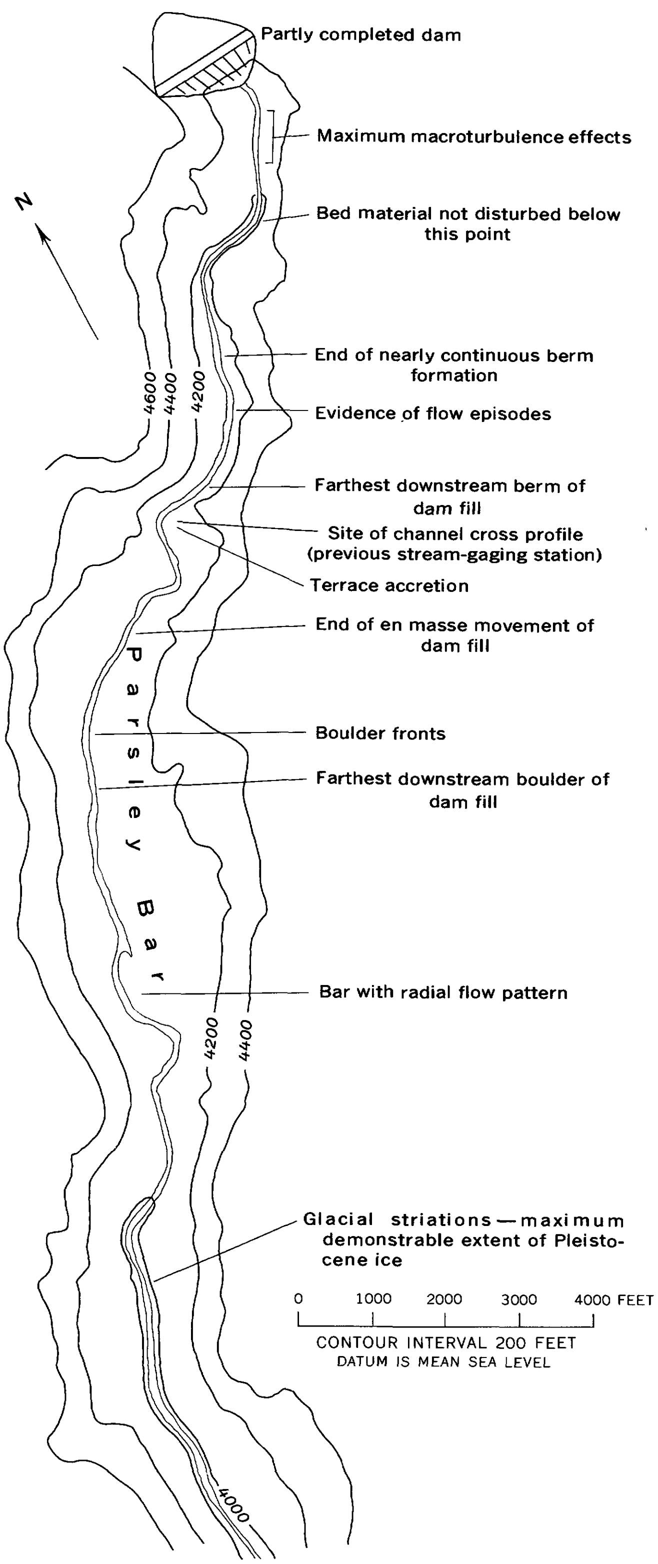


FIGURE 3.—Location of physical features in the reaches below the Hell Hole damsite pertaining to the study. Evidence of flow episodes shown on figure 20; site of channel cross profile, figure 11; bar with radial flow pattern, figure 17.

the Calaveras Formation of late Paleozoic age and, farther downstream, into the Mariposa Slate of Mesozoic age which is complexly faulted against amphibolite, chlorite schist, and assorted greenstones of the Amador Group of Mesozoic age.

Major structural trends are northwest-southeast and are part of the Mother Lode belt in the western half of the area, but are more nearly east-west in the reaches close to the dam. Shear zones and fractures trend slightly north of west and show no determinable direction of slip. A conjugate set of joints and extension fractures into which aplite and pegmatite dikes have been introduced is apparently the basic structural control of the channel trends. Conspicuous joint sets trend approximately east-west and north-northeast.

GEOMORPHIC HISTORY AND STRATIGRAPHY OF THE RUBICON CANYON

The Rubicon and Middle Fork American Rivers are bedrock gorges incised within a west-sloping erosion surface of Tertiary age, remnants of which form the divides on the west flank of the Sierra Nevada. Incision that accompanied the Pliocene and Pleistocene uplift and tilting of the range allowed the major trunk streams, such as the Rubicon, to maintain a westerly course normal to the dominant structural lineaments. Minor tributaries, however, show a high degree of structural control, particularly along the western flank of the range where their flow is parallel to the north and northwesterly shear system. Some apparent bedrock meanders in upper reaches of the Rubicon are attributed to the combined influence of regional slope and transverse joint sets. Various strath terrace levels on gorge sides represent fluctuations in the process of valley incision.

A poorly defined remnant of what Matthes (1930, p. 32) calls the "mountain-valley" stage of Sierra Nevada development is present as a series of matching slope inflections that probably represent terrace remnants at a level of approximately 1,600 feet above the river and 800 feet below the plateau surface in the vicinity of the downstream end of the Rubicon River. Within the upper section of the Rubicon are remnants of two former levels, one at 15–30 feet and one at 45–60 feet above the present channel thalweg. The lower of these, and possibly the upper as well, represent valley widening by glaciation, followed by cutting of the notch that locally confines the present channel.

The Rubicon River canyon was glaciated downslope at least to an elevation of 3,975 feet, three-fourths of a mile below Parsley Bar, as indicated by glacial striations and glacially shaped asymmetrical bosses on the bedrock surface. The valley form and gradual transition from a broader to a narrower channel suggest glaciation to an elevation of 3,650 feet. Striations are also present on bedrock spurs at the head of Parsley Bar and 700 feet below its downstream end. The lowest of the glacial benches is marked by glacial flutings and large, melt-water-scoured potholes.

Parsley Bar, an alluviated valley flat 1,900 feet in maximum width, is the most notable of many small areas of glacial and glaciofluvial deposition present in wider reaches. A composite stratigraphic column of the deposits in the cutbanks of Parsley Bar and the rest of the glaciated upper part of the flooded channel is presented in figure 4. These deposits contain an abundance of extremely coarse material, supply of which has been a controlling factor in the depositional pattern resulting from the flood surge.

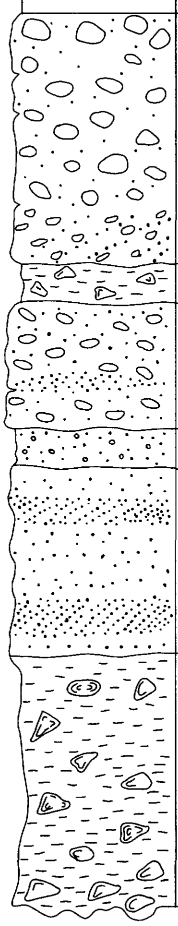
LITHOLOGY	THICKNESS, IN FEET	DESCRIPTION
	0–20	Cobble-boulder gravel, sand matrix; commonly horizontally stratified, some large-scale crossbedding; coarsest material at top; scour channels, sand lenses.
	0–3	Mudflow or till, similar to lower till; thinner weathering rinds; great lateral extent.
	0–10	Pebble-cobble gravel, rust-colored; sand matrix; inclined and contorted bedding, some crossbedding, sand lenses.
	0–3	Granule gravel, rust-colored, crossbedded.
	0–15	Sand and silt, white to rust, poorly consolidated, relatively well sorted; torrential and trough crossbedding.
	0–18	Till resting in pockets on glacially scoured, striated surface; gray-green mud and silt with angular dispersed clasts. Granitoid clasts are highly decomposed.

FIGURE 4.—Composite stratigraphic column of the deposits in the upper Rubicon River canyon. Maximum thickness exposed at any site is 58 feet.

EMBANKMENT FAILURE AND RELEASE AND DOWNSTREAM PASSAGE OF SURGE

Hell Hole Dam, a major component of the multipurpose Middle Fork American River Project, is an inclined-core rockfill dam, 410 feet high and 1,570 feet long at the crest, which required an estimated 8,800,000 cubic yards of material. The events resulting in failure of the partly completed structure and release of the flood surge were documented by an engineering consulting board in 1965 at the request of the construction supervisors, McCreary-Koretsky Engineers. The following description is based on that documentation and data supplied by W. A. Scott, sheriff-coroner of Placer County, I. L. Van Patten, assistant resident engineer at the damsite, and local newspaper coverage of the event.

A cross section of the stage of completion at the time of failure (fig. 5) indicates that the downstream rockfill had been completed to an elevation of 4,470 feet, 220 feet above the streambed. The impervious earth core, to act as a seal on the upstream side of the main supporting rockfill, had been placed to an elevation of 4,300 feet, approximately 50 feet above the streambed, at the time of the storm. Impoundment of storm runoff had reached the level of the core crest by 1:30 p.m., December 21, 1964, and only 34 hours later the water level had moved an additional 72 feet up the face of the pervious rockfill. Water began flowing through the rockfill shortly after the core was overtopped, and flow increased as the level rose.

During the early morning darkness of December 23, erosion of the toe of the structure began and was accompanied by progressive raveling of the downstream face of the embankment. Water was still rising on the upstream face and at 9:30 a.m. had reached a depth of 150 feet against the entire structure and 100 feet against the unprotected rockfill. At this time, continuous slumping had sufficiently reached the downstream face of the dam for water to top the eroded crest (fig. 6). Once overtopped, the loose rockfill was rapidly reduced, and the surge was expelled in 1 hour at an average flow of 260,000 cfs (cubic feet per second).

As the massive surge began its passage through the 61 miles of uninhabited canyon, officers of the Placer County Sheriff's Office were dispatched to access and observation points. They reported a slow initial rise, followed by a "terrific amount" of debris, mainly logs but including trailer houses, a shack, and assorted tanks and drums, followed by the wave, rising at about 2 feet per minute. Four of the five downstream bridges collapsed. The State Highway 49 girder bridge broke up rapidly and dropped into the river, but, just downstream, the unused Portland-Pacific Cement Co. bridge, constructed in 1910 and one of the first multiple-arch

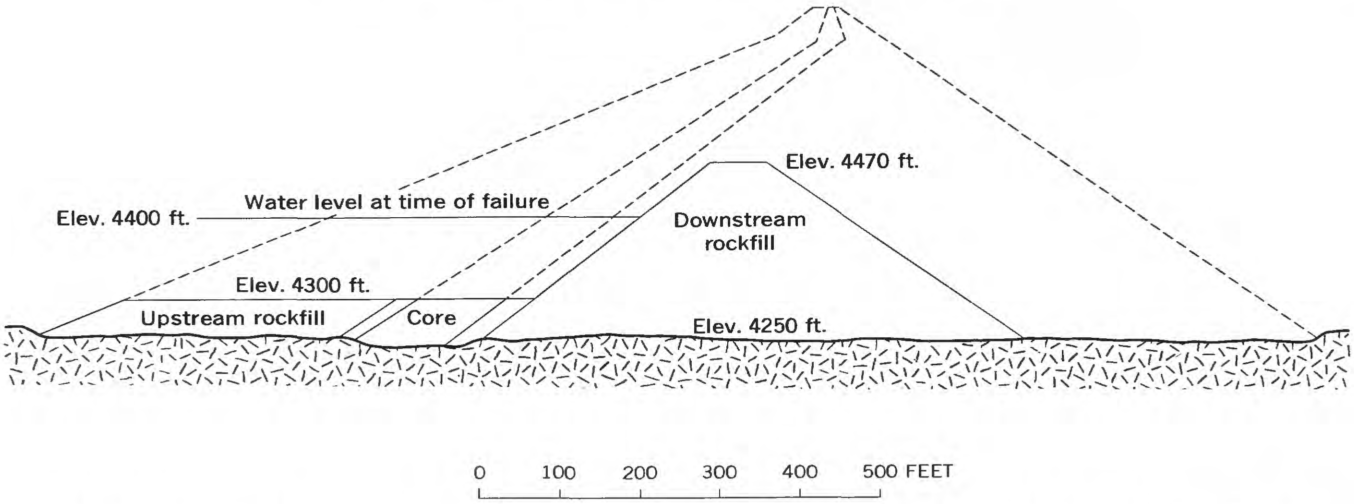


FIGURE 5.—Cross section of the completed Hell Hole Dam (dashed lines) and the stage of construction at the time of failure (solid lines).

FIGURE 6.—Breaching of the rockfill embankment at the Hell Hole damsite near time of peak discharge. View at 9:45 a.m., December 23, 1964. Note angularity of freshly quarried diorite, left. Photograph courtesy of McCreary-Koretsky Engineers, San Francisco, Calif.

spans on the west coast, did not fail. Four of the five stream-gaging stations were also obliterated. The surge was finally contained in Folsom Lake at about 1:30 p.m., having traversed the route from the dam at an average speed of 22 feet per second (15 miles per hour).

At the damsite, 726,000 of the 2,100,000 cubic yards of emplaced downstream rockfill (fig. 5) had been washed down the channel. Approximately 130,000 cubic yards of this detritus was subsequently recovered from the reach extending approximately 1,800 feet downstream from the dam where the material had accumulated to a depth of 30–40 feet. The partly completed core, however, was not eroded. Sedimentological measurements were made starting at the point in the channel below which rock-recovery operations had not destroyed the continuity of the deposits.

FLOOD OF DECEMBER 21–23, 1964, IN THE RUBICON RIVER BASIN

THE STORM

The flood-producing rains of late December in the Rubicon River basin began with fairly heavy precipitation early on December 19, under meteorological conditions that gave no indication that storms of unusual intensity would follow. The Pacific high, a high-pressure airmass, occupied most of the ocean area between Hawaii and Alaska and effectively blocked the migration of moist tropical air to the west coast. Because the storm track lay around the north side of the Pacific high, from the Gulf of Alaska to Oregon and northern California, the storm of December 19–20 was accompanied by low temperatures that brought snow to the higher elevations.

On December 20, the Pacific high was undergoing progressive erosion in the subtropics northeast of Hawaii. This erosion allowed subsequent storms to move across the Pacific Ocean at successively lower latitudes before turning toward the west coast. A storm track, 500 miles wide, was thus established from the western Pacific near Hawaii to Oregon and northern California. Concurrently an extemely cold mass of air from the Arctic region met the warm moist air about 1,000 miles west of the coast and intensified the storm systems as they moved rapidly toward the mainland. The combined effect of moist unstable airmasses, strong west-southwest winds, and mountain ranges oriented nearly at right angles to the flow of air resulted in torrential rainfall from December 21 to 23. During this period temperatures rose sharply. The freezing level rose to elevations of 10,000 feet, and therefore almost all precipitation over the Rubicon River basin was in the form of rain.

There are no precipitation gages in the basin, but from precipitation records for stations in the surrounding area (fig. 1), it is estimated that the basin upstream from the damsite received 22 inches of precipitation in the 5-day period, December 19–23. Figure 7 shows hourly precipitation for four stations in the general region of the Rubicon River basin. From these data and generalized elevation-precipitation relations for the Sierra Nevada, it is deduced that the basin upstream from Hell Hole Dam received the following maximum amounts of precipitation in the periods indicated:

Duration period (hours)	*Maximum precipitation (inches)*
1	0.6
12	4.5
24	8
48	14

THE FLOOD

Antecedent conditions were favorable for heavy runoff from the storms of late December. Precipitation had been greater than normal during the month of November, and the occasional rains that occurred during the first half of December maintained soil moisture at high levels. The potential for rapid runoff was further increased by the low temperatures of mid-December that caused freezing of the ground at the higher elevations.

A substantial snowpack had accumulated in the mountains prior to the heavy precipitation of December 21–23, but melting snow is believed to have had only a minor effect on the flood peaks that resulted from the December storms. On December 20, about 20 inches of snow lay on the ground at the 6,000-foot level. On that day, the U.S. Weather Bureau reported 67 inches of snow on the ground at Twin Lakes, elevation 7,829 feet, south of the Rubicon River basin. By December 24, the depth of the snowpack at Twin Lakes had diminished to 42 inches. No data are available concerning the water content of the snowpack, but much of the 25 inches of reduction of depth at Twin Lakes was probably due to compaction. Preliminary analysis of the Sierra Nevada floods by the U.S. Army Corps of Engineers and by the California Department of Water Resources has indicated that over most of the snow-covered area the heavy rainfall and associated meteorological conditions during the storm generally supplied only enough heat to ripen the snowpack. This ripening means that the snowpack became isothermal at 32°F and became sufficiently dense to retain a small percentage of free water in the capillary spaces in the pack. The net result was that most of the snowpack had little effect on the peak runoff, in that it contributed little melt and offered little delay to the rain passing through it. However, at lower elevations where the snowpack was too light to resist melting by the rain, the melt augmented runoff. On the other hand, at the higher elevations where the snowpack was very

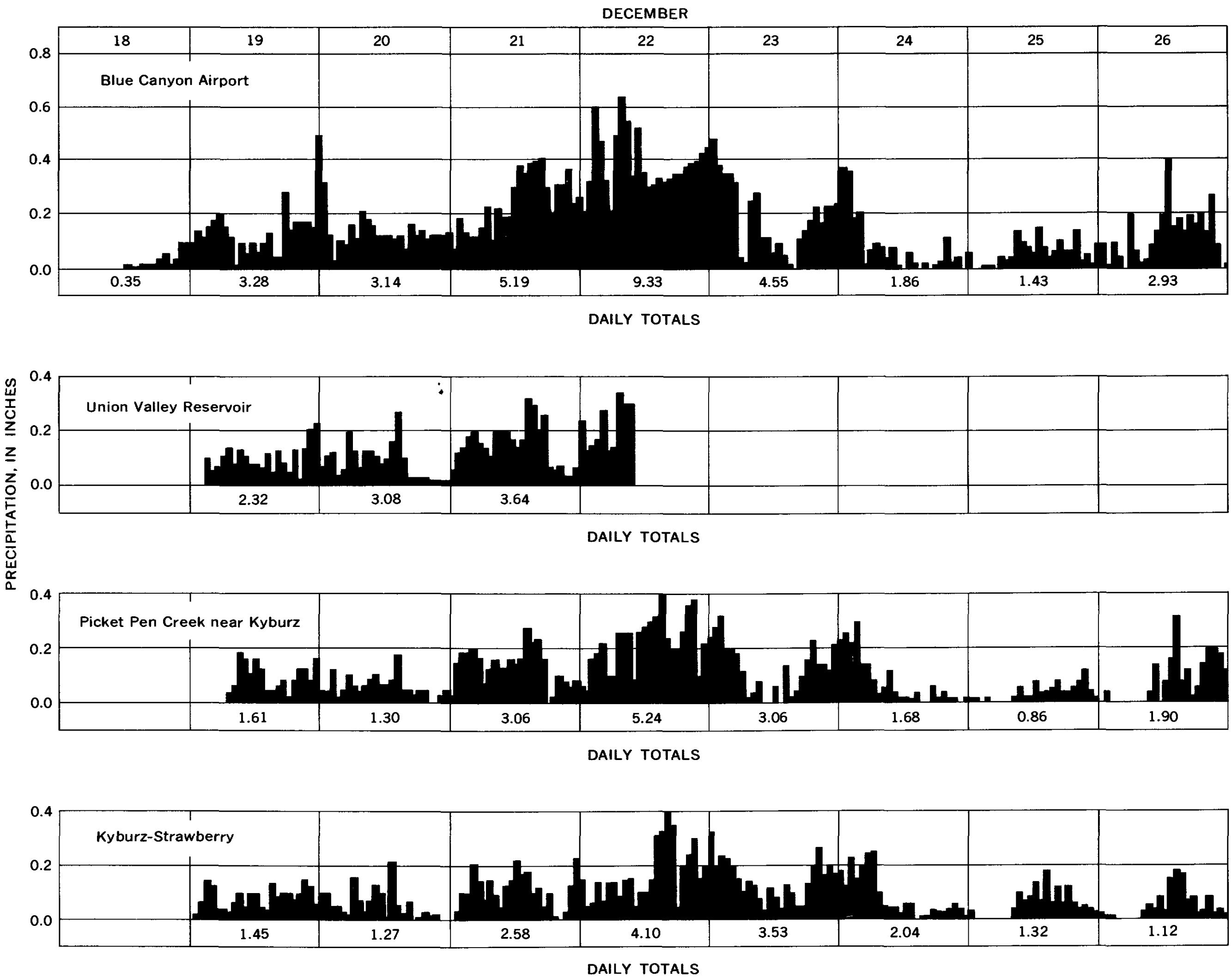


FIGURE 7.—Hourly precipitation at stations nearest the Hell Hole damsite for the period December 18–26, 1964.

heavy, the pack absorbed rain and actually reduced runoff.

The runoff in response to the intense rain of December 21–23 was dramatic, and streams everywhere rose rapidly. This was the third time in 9 years that the Rubicon River basin had been deluged, and, if it were not for the primitive state of development of most of the region, damage on each occasion would have been catastrophic. The first of the three floods occurred in December 1955, but the peak discharges of that flood, the greatest recorded until that time, were exceeded in the flood of January 31–February 1, 1963. The flood of December 1964 had peak discharges that were roughly equivalent to those of the flood of 1963 in the general area. Three- and five-day periods of maximum storm runoff for the 1964 flood were 109 and 146 percent of the 1955 values, the largest previously recorded. Peak stages and discharges for the three floods at gaging stations on the Rubicon River mainstem and lower Middle Fork American River are listed in table 1. Also included in table 1 are estimated recurrence intervals for the floods at these five stations, as determined from a statewide flood-frequency study by Young and Cruff (1966).

Of the three gaging stations on the Rubicon River mainstem (fig. 1), only that at Rubicon Springs is upstream from Hell Hole Dam. This station was established after the 1955 flood, and consequently no hydrograph is available for that flood, although its peak discharge had been computed from floodmarks at the site. Complete hydrographs are available, however, for the floods of 1963 and 1964. The Rubicon River station near Georgetown was operative during the 1955 flood, but was destroyed both in 1963 and 1964, and consequently, hydrographs are not available for the last two floods. The Rubicon River station near the river mouth (near Foresthill) was established after the 1955 flood, and it too was destroyed both in 1963 and 1964.

TABLE 1.—*Summary of flood stages and discharges*

Gage	Stream and place of determination	Maximum flood			
		Date	Gage height (ft)	Discharge (cfs)	Recurrence interval (times>100-yr flood)
		Rubicon River			
4280	Rubicon River at Rubicon Springs.	Dec. 1955	13.0	9,270	1.20
		Feb. 1963	14.28	11,500	1.49
		Dec. 1964		[1] 11,300	1.47
4310	Rubicon River near Georgetown.	Dec. 1955	18.76	51,000	1.46
		Feb. 1963	25.8	58,000	1.66
		Dec. 1964	71.1±		
4332	Rubicon River near Foresthill.	Feb. 1963	35	83,000	1.54
		Dec. 1964	78		
		Middle Fork American River			
4333	Middle Fork American River near Foresthill.	Feb. 1963	38	113,000	1.20
		Dec. 1964	61	[2] 310,000	3.30
4335	Middle Fork American River near Auburn.	Dec. 1955	33.9	[3] 79,000	.34
		Feb. 1963	43.1	[3] 121,000	1.06
		Dec. 1964		[4] 83,600	.38
			60.4	[5] 253,000	2.22

[1] Adjusted for storage and diversion.
[2] 1964 discharge conputed by slope-conveyance method.
[3] Old site; about 1,000 ft upstream from present site.
[4] Natural flow prior to surge.
[5] Surge.

Of the two gaging stations on the Middle Fork American River, that near Foresthill, just below the mouth of the Ribucon River, was established after 1955 and destroyed in 1964. Consequently, the only one of the three flood hydrographs available for this station is that for 1963. The station on the Middle Fork American River near Auburn operated during the floods of 1955 and 1964, and flood hydrographs are therefore available for those years. The station was destroyed, however, by the flood of 1963.

Because there are no concurrent hydrographs for any of the three major floods at successive gaging stations on the Rubicon River mainstem and lower Middle Fork American River, flood-routing procedures could not be developed to compute the hydrographs for the flood wave of December 1964 at the destroyed gaging stations. Furthermore, the lack of precipitation stations in the affected basins precludes the use of rainfall-runoff relations for reliable computation of inflow into the reaches between gaging stations, for use with any flood-routing procedures that might be developed. Some rather crude methods were used, therefore, to compute the inflow and outflow hydrographs at Hell Hole Dam and the peak discharge at stations downstream from the damsite.

INFLOW AND OUTFLOW AT HELL HOLE DAM

The only data available for computing inflow and outflow at Hell Hole Dam were a record of storage of impounded water behind the dam during the flood period (fig. 8) and a chronology of the dam failure, both supplied by McCreary-Koretsky Engineers. It was essential that the inflow hydrograph be synthesized, because with an inflow and storage record, the outflow hydrograph could be computed from the equation for conservation of mass:

$$\text{Outflow} = \text{Inflow} \pm \text{change in storage.}$$

The obvious method of computing the inflow hydrograph would be by means of a rainfall-runoff relation, such as the unit hydrograph, which could not be used because of the lack of rainfall records in the basin. The method finally used to compute inflow involved a relation between natural discharge of the Rubicon River at Rubicon Springs (31.4 sq mi) and at Hell Hole Dam (120 sq mi). This relation, in turn, was derived from a relation between natural discharge of the Rubicon River at Rubicon Springs and discharge of the Rubicon River above the mouth of South Fork Rubicon River (135 sq mi). The discharge of Rubicon River above the mouth of South Fork Rubicon River was obtained by subtracting the gaged discharge of South Fork from the gaged discharge of the Rubicon River near Georgetown. The net result of the analysis was the equation:

$$\text{Inflow at Hell Hole Dam} = 3.5 \times (\text{discharge at Rubicon Springs, adjusted for storage and diversion})$$

From this equation, the inflow hydrograph at Hell Hole Dam was computed (fig. 8), its peak discharge being 39,000 cfs.

A check of the inflow hydrograph was made by examining the area under the hydrograph for the storm period December 20–27. A basic premise implied in the derivation of this hydrograph was that storm runoff, in inches, of the Rubicon River at Hell Hole damsite was closely equivalent to the storm runoff of the Rubicon River near Georgetown. Furthermore, runoff records for the past 15 years show that during major storms, the storm runoff at the Georgetown station was 1.25 times as great as the storm runoff of Silver Creek at Union Valley Dam (fig. 1). For the period December 20–27, 1964, a storm runoff of 16.97 inches for Silver Creek indicates a corresponding storm runoff of 21.21 inches for the Rubicon River near Georgetown. This runoff value for the Georgetown station closely checks the volume of inflow—21.24 inches—under the hydrograph for Hell Hole Dam.

The computed inflow hydrograph and the record of storage at Hell Hole Dam were used, as explained above, to compute the outflow hydrograph. The outflow hydrograph, also shown in figure 8, shows that the discharge attained a maximum 1-hour mean discharge of 260,000 cfs when the embankment was breached.

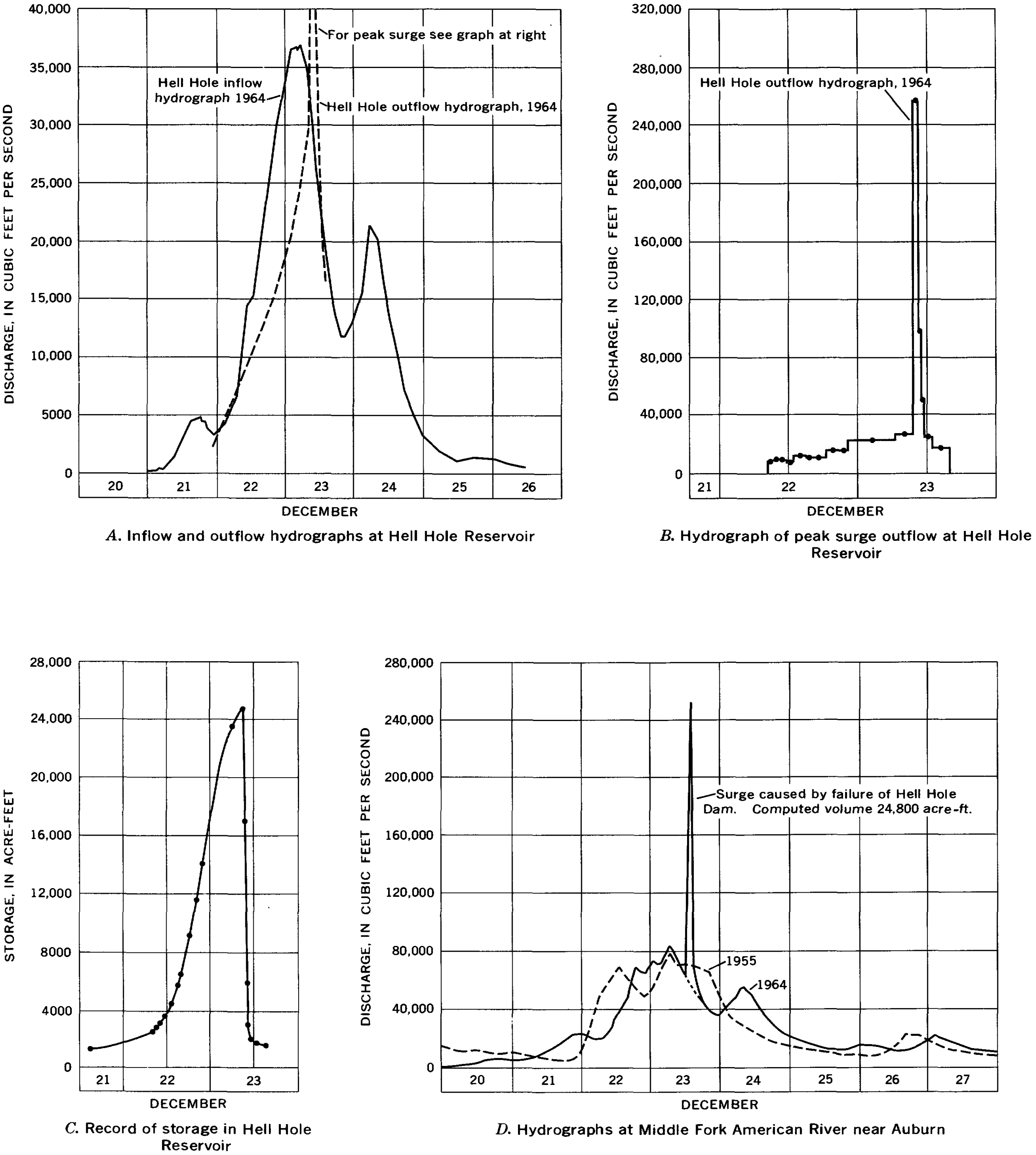


FIGURE 8.—Flow and storage data associated with the failure of Hell Hole Dam in December 1964.

PEAK DISCHARGE OF THE SURGE DOWNSTREAM FROM HELL HOLE DAM

In the absence of a reliable procedure to route the flood wave from Hell Hole Dam to downstream gaging stations, the slope-conveyance method was used to compute peak discharge. The basic equation in the method is the Manning equation:

$$Q=KS^{1/2}, \tag{1}$$

where Q is peak discharge, in cubic feet per second,
K is conveyance, in cubic feet per second, and
S is the slope of the energy gradient.

The conveyance, K, is determined from the geometry and roughness of the channel, by means of the equation:

$$K=\frac{1.486}{n}AR^{2/3}, \tag{2}$$

where n is the Manning roughness coefficient,
A is cross-sectional area, in square feet, and
R is hydraulic radius, in feet, or cross-sectional area divided by cross-sectional wetted perimeter.

In the slope-conveyance method, the assumption is made that the energy slope at a site is constant for all extremely high stages. Therefore, if the discharge at some high stage (Q_1) is known, the discharge at some higher stage (Q_2) can be computed from the ratio of the conveyances at the two stages, where

$$Q_2=Q_1(K_2/K_1). \tag{3}$$

If there is no overbank flow at either of the two discharges, the values of n_1 and n_2 will probably be equal to each other in which case equation 3 can be further simplified to:

$$Q_2=Q_1(A_2R_2^{2/3}/A_1R_1^{2/3}). \tag{4}$$

Equation 4 was used to compute the 1964 peak discharge (Q_2) at the gaging station on the Middle Fork American River near Foresthill (table 1) which was destroyed by the flood. At this station, the 1963 peak stage and discharge (Q_1) were known, as well as the 1964 peak stage.

The gage on the Middle Fork American River near Auburn operated throughout the flood and strikingly shows the surge caused by the failure (fig. 8). The computed volume of water in the surge is 24,800 acre-feet at this station.

ATTENUATION OF SURGE WAVE

Numerous approximations of stage, made by hand level throughout the flood course, indicate that the height of the flood wave decreased at a fairly constant rate between the dam and Parsley Bar and again in the reaches between the Rubicon gorge and Folsom Lake. Wave Height increased below Parsley Bar, reaching a maximum in the confining narrows of the Rubicon gorge and reflecting the gradual narrowing of the channel downstream from Parsley Bar.

The peak discharge of the surge also decreased downstream. The peak on the Middle Fork American River near Foresthill, computed by the slope-conveyance method, was 310,000 cfs (table 1). Downstream, peak flow near Auburn was 253,000 cfs, including a natural flow of approximately 60,000 cfs in the river just before the surge. Trial application of the slope-conveyance technique at the three upstream gaging stations which were destroyed by the surge suggested that larger discharges occurred there. There is no way, unfortunately, of estimating the momentary peak release at the damsite which was certainly substantially greater than the maximum 1-hour average flow of 260,000 cfs (fig 8).

Because breaching of the dam was not instantaneous, release from the reservoir was sufficiently retarded so that the surge did not immediately attain its peak discharge. There was apparently no development of a bore or breaking front to the wave during any part of the downstream flow. Average velocity of the wave, approximately 22 feet per second (or 15 miles per hour) over the entire route, was determined by map measurement of longitudinal distance in the channel thalweg and from the time that the main mass of forest debris uprooted by the surge entered Folsom Lake.

EROSIONAL EFFECTS OF THE SURGE

Sedimentary deposits in and along the channel were severely eroded by the surge. Deposits affected by the flood wave include, in approximate order of magnitude: (1) Alluvial deposits, of both Pleistocene and Recent age, (2) colluvium, including material from landslides triggered by the surge, (3) soil, and (4) bedrock. Erosion of the terrace gravel of Pleistocene age was dominantly by lateral cutting rather than surface scour, probably because the surface of the deposits was armored by a mat of vegetation (fig. 9). A surprisingly small amount of bedrock plucking occurred, but notable expanses of bare scoured bedrock surfaces, particularly in the gorge of the Rubicon, give the impression of extensive removal of joint-bounded blocks. Wherever preflood control is present, as at bridge and gaging-station sites and as evidenced by comparison of preflood photographs with the present channel, only a minor amount of bedrock removal can be proved. Striations and percussion marks formed by cobbles and boulders carried by macroturbulence are common on the bedrock surfaces up to the high-water mark in the interval

FIGURE 9.—Lateral supply of sediment to the flood channel from a deposit of terrace gravel and till, 3.3 miles downstream from the damsite.

from the damsite to approximately 1,200 feet down the channel.

Stands of mature yellow pine, cedar, and Douglas-fir were removed by the surge, the maximum loss of timber occurring in the Parsley Bar area. Many of the trees were 250–400 years old. A large yellow pine and a cedar felled by the flood wave were 351 and 390 years old, respectively. Jams of timber within the channel were relatively rare. Several formed in the 4-mile reach below Parsely Bar, but most of the vegetal debris traveled the complete route to Folsom Lake. A few trees in the upper reaches were killed by bark removal. The maximum abrasion of tree trunks by suspended rock fragments was generally in a zone from 3 to 5 feet above the present aggradational surface (fig. 10). Below this level, the trunks may have been protected by temporary burial. Even in the lower reaches of the flood course, the discharge was clearly of a high recurrence interval. Possibly late 19th century placer tailings were removed from Poverty Bar, Cherokee Bar, and uppermost Oregon Bar, all on the Middle Fork American River.

EFFECTS ON CHANNEL MORPHOLOGY

The five gaging-stations sites along the flood course at which channel cross profiles had been previously measured were resurveyed. Changes in channel morphology wrought by the surge decreased downstream as discharge and recurrence interval of the surge decreased. Comparison of two presurge surveys at each of two of the cross-profile sites shows that the bulk of the observed change was in fact related to passage of the surge and not to normal annual fluctuations.

A summary of the channel modifications and stage at each station is presented in table 2. Change is most evident at the station farthest upstream where the pronounced aggradation in the thalweg is related to downstream movement of rockfill from the dam (fig. 11). Deposits on the glacial-outwash terrace at this station, however, contain very little material derived from the dam, and therefore occurred at an early stage of the surge. The other cross profiles exhibit thalweg aggradation that is unrelated to deposition of the dam rockfill.

The cross profiles and field observations suggest that much colluvium, locally containing very coarse material,

FIGURE 10.—Trees showing maximum abrasion level 3–5 feet above present ground surface. Perched boulder is 3.4 feet in intermediate diameter. View is looking downstream, approximately 4 miles below the damsite.

has been stripped from the base of steep valley side-slopes adjoining the bedrock channel which probably have not been awash since glacial recession. Slumping of boundary terrace deposits into the channel resulted from undercutting. Most of this locally derived sediment was apparently introduced into the flow on the receding stage when competency was continuously decreasing. Therefore, far more material was supplied to the channel than could be transported, and much of the extremely coarse material supplied from the sides of the channel was either not moved or moved only short distances. Thus, a chief effect of this short-period catastrophic surge was to introduce coarse sediment from lateral deposits into the active stream channel with a resulting net aggradation in the thalweg.

In short, the effect in terms of cross profile was to modify a V-shaped channel to a more nearly U-shaped channel. The surge altered the channel radically in confined reaches and moved, at least for short distances, a large proportion of the material previously present in the channel. Although only five cross profiles are a meager record on which to generalize, deposition in the thalweg may have been nearly continuous along the entire flood route.

MASS MOVEMENTS CAUSED BY THE SURGE

The surge triggered massive landslides as it progressed downstream and undercut valley side-slopes. Most of the slope failures were at the outer bank of channel bends where velocity and water depth were greatest. Large slides were confined to the steep-sided gorge of the Rubicon, which is cut in slaty metamorphic rocks of the Calaveras Formation. The steepness of these slopes, which have a deep regolith, is attributed partly to the nearly vertical attitude of the bedrock. At the time of surge passage, the slopes had been exposed to approximately 48 hours of continuous rain and were saturated so that conditions were ripe for slope failures. Although evidence of soil creep is general, there are virtually no recent scars of previous major earthslides in the canyon.

The slope failures are commonly triangular in plan view and the largest has a maximum toe width of 630 feet. Slide scars reach a maximum elevation of 500 feet

TABLE 2—*Description of channel cross profiles*

Location of stream-gaging station	Distance downstream from damsite (miles)	Peak stage (ft) 1963	Peak stage (ft) 1964	Description of flow cross profile and channel	Approximate change in thalweg elevation (ft)	Changes in cross profile
Rubicon River below Hell Hole Dam. (See fig. 11.).	1. 3	21. 5	53. 5	Lateral bedrock control, 675 ft wide; alluvial fill, 375 ft wide. Glacial-outwash terrace comprises left half of fill.	+7. 0	Aggradation in thalweg; 125-ft lateral movement of thalweg; accretion on terrace surface; probable bedrock removal on right bank.
Rubicon River near Georgetown.	8. 9	25. 8	71. 1	Lateral bedrock control, 400 ft wide; alluvial fill, 250 ft wide. Left bank cut in glaciofluvial and colluvial deposits.	+1. 5	Aggradation in thalweg; 50-ft lateral movement of thalweg; deposition of large boulder bar on right side of channel. No erosion of bedrock.
Rubicon River near Foresthill.	26. 3	35. 0	78. 2	Lateral bedrock control, 255 ft wide; alluvial fill, 135 ft wide and probably quite shallow.	+2. 5	Aggradation in thalweg; no lateral displacement of thalweg; addition to boulder bar on left side of channel. Possible slight removal of bedrock.
Middle Fork American River near Foresthill.	35. 6	38. 0	61. 1	Lateral bedrock control, 378 ft wide; alluvial fill, 260 ft wide.	+3. 0	Aggradation in thalweg; 20-ft lateral displacement of thalweg; addition to coarse bar on left side of channel. No removal of bedrock.
Middle Fork American River near Auburn.	54. 5	[1] 43. 1	60. 4	Only basal part of section was resurveyed.	+. 2	Slight aggradation in thalweg but as much as 3.0 ft of aggradation in other parts of channel, addition to coarse bar on left side of channel. No determinable removal of bedrock.

[1] Old site; about 1,000 ft upstream from present site.

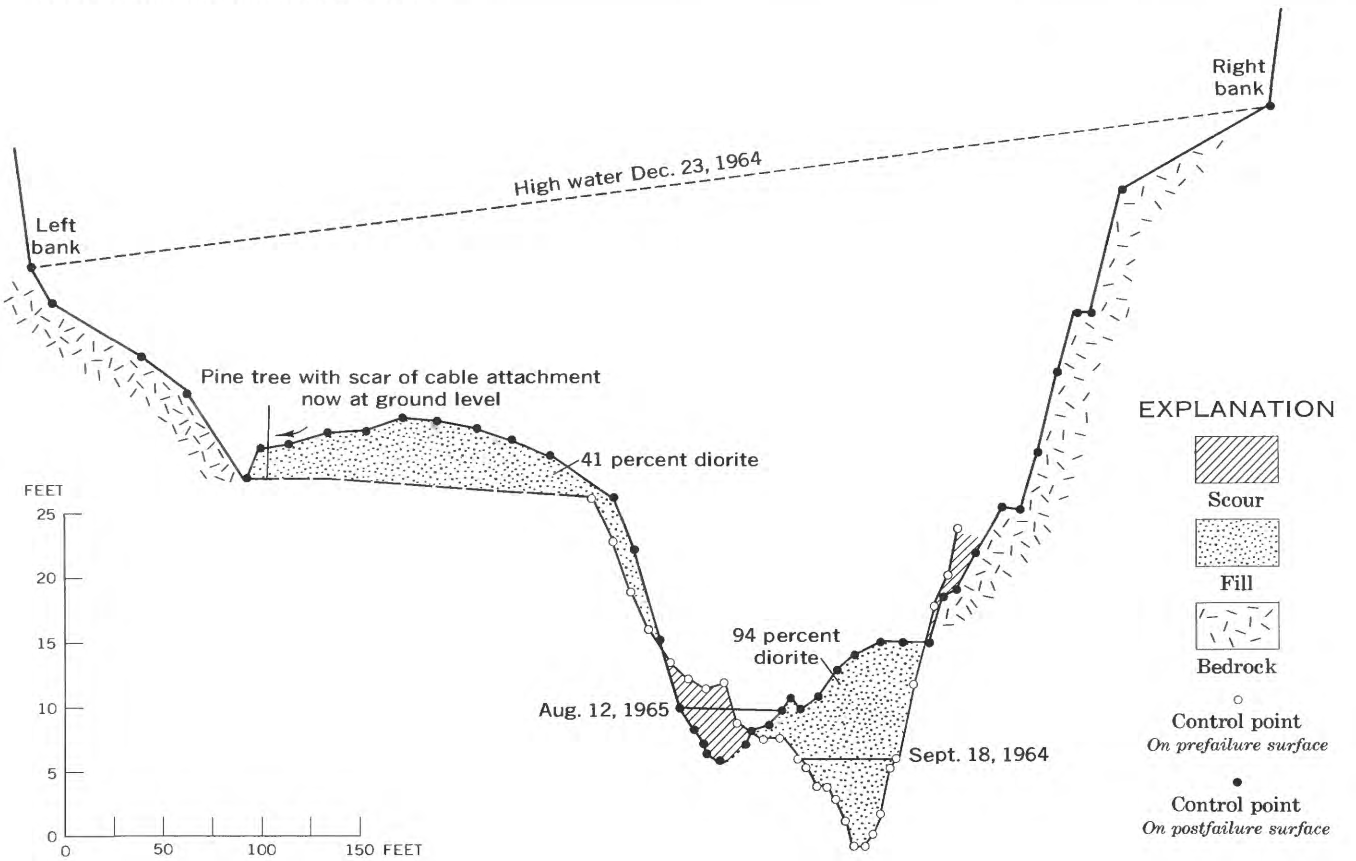


FIGURE 11.—Prefailure and postfailure cross profiles of the channel at the site of the first gaging station reached by the surge, Rubicon River below Hell Hole Dam, 1.3 miles downstream.

FIGURE 12.—Base of the largest slide in the Rubicon gorge, 0.5 mile downstream from the mouth of Little Grizzly Canyon, 18.7 miles downstream from Hell Hole damsite. Note scour due to surge at right, the downstream direction. Helicopter, right, indicates scale.

above the channel. The slide that involves the greatest volume of displaced material is linear in plan view and has a nearly constant width of about 300 feet. It originated in a spoon-shaped rupture approximately 400 feet above the bottom of the gorge (fig. 12). In addition to the large slides, nearly continuous sliding and slumping of colluvium on a smaller scale occurred along channel banks within the gorge.

Slides are identified as the slow-earthflow and the debris-avalanche type described by Varnes (1958). At the heads of several slides, individual blocks of bedrock moved by slip, but such block slumping was transitional to movement by earthflow and debris avalanche in the lower part of the slides. Most of the slides began as mass movements of semiconsolidated material and were soon transformed downslope to flows.

The largest slides occurred after the surge peak and thus did not contribute significantly to the sediment load of the flood. Movement of some slides probably began before arrival of the flood peak, and the removal of detritus from the toe of the slide allowed renewal of movement. Most of the smaller slides were probably directly triggered by erosion near the flood peak and were virtually coincident with passage of the surge. Presence of highest scour lines on some slides at levels substantially below the high-water mark shows that sliding continued during and after flood recession. Virtually all the landslips were closely related to the surge passage, and most of the slides were directly triggered by the flood wave. Probably comparable saturation conditions resulting from storms of 1955 and 1963 produced little or no sliding. As discussed on page M36, the destruction of slope equilibrium by the surge of 1964 also resulted in renewed sliding a year later during the next rainy season.

Even the largest slide did not appreciably dam the channel. The present low-water channel cuts through as much as 7 feet of slide detritus and lateral levees of slide detritus (fig. 12) are present downstream from the slide. Measurements of floodmarks immediately upstream showed a maximum depth of 62.3 feet and those downstream, 63.5 feet, in a comparable channel. Thus, the peak flow apparently was not affected by the slide, and most of the movement was during the recession phase.

Determination of the surface area of three of the largest slides and estimation of the depth, for slumped parts of slides as described by Philbrick and Cleaves (1958), permitted an estimate to be made of the volume of material in each slide. Seismic measurements of depth were available for one of the three slides. Extension of these estimates to 29 other slides, on the basis of relative size as measured on aerial photographs, yielded an order-of-magnitude approximation of the total amount of material involved in landslides resulting from the flood—800,000 cubic yards—a surprisingly small figure and an estimate subject to large sources of error.

Only a small part of this volume was actually contributed as sediment to the flood. The time relation of sliding to the flood crest, armoring of the debris avalanches by extremely coarse material at the surface, and coherence of the mud snouts of the flows prevented much erosion by the flood. The percentage of material eroded from each slide by the surge was estimated principally on the basis of aerial photographs and, for about a third, on the basis of field observations. Less than 30 percent of the total slide volume was removed by the flood. Eroded colluvium and the inestimable quantity of detritus supplied by continuous small-scale sliding that occurred in steep-walled reaches were almost certainly more important as sources of sediment. Virtually all the latter material was moved by the flood.

DEPOSITIONAL FEATURES

METHODS OF STUDY

Depositional forms were studied in the field and by analysis of large scale (1:1,200) aerial photographs, obtained for the 4 miles of channel downstream from the damsite. Additional photography was made of the remainder of the flood channel at a scale of 1:6,000. The photography was made between August 28 and September 10, 1965. A comparison with two sets of preflood aerial photographs was possible, one flown in September and October 1948, at a scale of 1:42,000, and another taken during July and August 1962, at a scale of 1:20,000. Approximately 12 miles of the poorly accessible canyon was covered on foot and the rest was traversed by helicopter. Channel forms from the dam

FIGURE 13.—Boulder berms preserved 0.7 mile downstream from the damsite. Note greater coarseness of material in center of channel. Flow is from left to right. Photograph by J. C. Brice.

to a point 5 miles downstream were studied and mapped by use of the large-scale photographs and 7½-minute topographic maps enlarged three times as base maps.

LATERAL BERMS OR TERRACES

The most striking depositional forms resulting from passage of the flood surge are terracelike berms composed of boulders of diorite from the dam rockfill (fig. 13). The nearly flat-topped berms occur continuously on both sides of the channel in the uppermost reach, but downstream they are confined to protected areas behind bedrock projections or the inner bank of bends. Berms composed of rockfill derived at the damsite are restricted to the upper part of the flood route, which ends 1.1 miles downstream from the dam toe.

The berm surface is as much as 28 feet above the present channel thalweg and decreases generally, but not regularly, downstream. Although subsequent artificial removal of material prevents exact determination, the level of the berms probably rose upstream nearly to the level of the dam core, 50 feet above the channel. At a point approximately 1,600 feet downstream from the dam, a pronounced inflection in the berm surface occurs. The surface does not correlate with a change in slope in the present thalweg, which is extensively aggraded in that reach, but may correspond to a slope change in the original channel or to a constriction in the temporarily clogged channel. In transverse section, the surface of the berms usually slopes gently toward the present channel, and where berms are present on both sides of the channel they occur at approximately the same level.

Another characteristic of the berms is the presence of the coarsest detritus at or near the surface (fig. 14). They are similar in this respect to the glacial-outwash terraces in the Rubicon River basin. This reverse grading of the deposits relates to the depositional dynamics, possibly to dispersive stress forcing larger particles to the surface during movement (Leopold and others, 1964, p. 211) rather than to occurrence of the coarser particles remaining as a lag deposit after removal of fines.

Generalization on the relation of the coarseness of the berms to the coarseness of material in the channel is not possible. In the reach immediately downstream from the dam, coarsest debris occurs in the center of the channel. Through the middle of the area of berm formation, in which the pool-riffle pattern becomes more pronounced,

FIGURE 14.—Section of berm parallel to stream channel in reach below Hell Hole damsite. Rucksack is at the base of the berm section. Note the coarse material at the top of the berm surface and the contrast in size with coarser material in center of channel, foreground. All material is diorite from the damsite.

berms may be either coarser or finer than the adjacent channel material, but all the berms are coarser than pool components. The berms farthest downstream are distinctly finer than the channel material.

The terracelike berms are superficially analogous to common alluvial terraces, formed by channel aggradation followed by incision of a lower channel. Generally, alluviation followed by erosion is a lengthy process. The fact that the terracelike berms were formed by a single flood event and that the bed material is almost entirely of boulder size, and thus, once deposited, would be unlikely to be eroded at a later, necessarily lower, stage suggests another origin for the coarse terracelike deposits.

Macroturbulent conditions transported boulders in suspension well above the berm surface; the evidence of such transport, perched boulders of rockfill diorite, is most conspicuous in the uppermost reaches of the flood channel which show extensive berm formation. The material composing the berms, however, was deposited from bedload, which locally moved as thick subaqueous debris flows or a series of gravel waves, in this section of the channel. The top of the continuous berms may represent the approximate level of bedload flow or wave movement attained in the main channel rather than any static aggradational surface. The degree to which the present channel below the berm surface represents incision by erosion at a later stage must remain an unknown, as must the configuration of the surface, whether static or dynamic, represented by the berms. The berm surface probably was continuous across the channel at one period during the surge. Bedload movement may have been continuous in the center of the channel and, as the material moved out of the reach, the present low-water channel could have been left as basically a depositional rather than an erosional feature. In terms of the time sequence of events only, the situation may be similar to that occurring in the formation of mudflow levees in which, just after a confined mudflow has peaked, continuing flow in the center of the channel moves most of the flow out of the reach, leaving terraces marking the peak on each side of the watercourse. Local presence of the coarsest material in the center of the channel is due to lagging of the largest particles well behind the peak volume of bedload movement. At least in the lower reaches of berm formation, both formation and incision or removal of the berms probably occurred during the receding stage. This probability is evidenced by relations at the cross-profile site (fig. 11) where material carried by the surge peak and then deposited on a high-level terrace included very little rockfill detritus.

All the berms described above are composed of damfill material. Downstream, similar but discontinuous isolated ridges of sand formed in areas of low velocity during the surge, particularly on vegetated banks. Such distinctly finer grained berms may be present within 10 feet of the high-water mark where the stage was approximately 50–60 feet. Also in a downstream direction, local terracelike berms formed by the surge and composed of normal alluvial gravel, including some detritus of boulder size, occur on point bars and behind bedrock projections on the Middle and North Forks of the American River. Thus, the berm-forming process is not solely related to the supply of sediment provided by the rockfill, but does relate generally to the large volume of sediment transported by the surge.

BOULDER BARS

The terracelike berms are transitionally replaced downstream by lobate bars. The bars are in part flat topped, consist of boulder-size material, and are the dominant depositional forms downstream. The upstream pattern of the bar trends is linear, parallel to the straight reaches between the damsite and Parsley Bar, and the apexes of the bars are directly downstream from bedrock projections within or lateral to the channel (fig. 15). As the channel becomes sinuous, the pitch of the surfaces of the bars alternates from one side of the channel to the other, as does the low-water channel (fig. 16).

In part of the uppermost section of the channel and at the downstream end of Parsley Bar, there is a medial bar or ridge of coarse material. The bar terminates in a frondescent or radial pattern with flow lines deviating as much as 50° on each side of the axis of the channel. The flow lines are not visibly related to channel configuration, a slightly contracting reach, but are marked distinctly on the aerial photographs by felled and lodged trees, textural changes, and ridges of bed material (fig. 17).

TERRACE ACCRETION

Addition of material on the surface of a terrace remnant near the head of Parsley Bar suggests that the flood had a greater magnitude than flows, presumably of Pleistocene age, that were responsible for transport of the terrace fill. As much as 5 feet of boulder gravel was added to the terrace remnant on the left bank at the site of the former gaging station, Rubicon River below Hell Hole Dam, 1.3 miles downstream from the dam (fig. 11). The flood did not aggrade the extensive terrace deposits of Parsley Bar or any terrace farther downstream.

The gravel added to the terrace upstream from Parsley Bar consists almost entirely of reworked terrace gravel derived from the margins of that terrace and

FIGURE 15.—Lobate bar formed downstream from a bedrock projection into channel at right. Central part of bar is mainly reworked terrace and recently deposited alluvial detritus. Secondary bermlike formation in foreground is predominantly rockfill from the dam embankment. View looking downstream 1.1 miles below the damsite.

from others upstream. However, two cored boulders of dam fill were observed in the deposit. The head of the terrace was eroded and a cutbank having a maximum height of 12 feet was formed, at the base of which the present channel fill is composed of diorite derived from the dam. The comparison of aerial photographs suggests that as much as 20 feet of lateral erosion occurred along the terrace margin.

BOULDER FRONTS

An arcuate boulder front 3–7 feet high extends 250 feet across the flood channel in the middle of Parsley Bar (figs. 18, 19). The front represents a point to which, at a late stage of the surge passage, boulders as much as 10.5 feet in intermediate diameter were transported, but beyond which little coarse material was moved. The boulder deposit transgressed across and only partly replaced a sand layer 2–8 feet thick that was deposited during an earlier interval of surge recession. Numerous small trees in growth position protrude through the sand layer which was molded into longitudinal and arcuate transverse dunes. Similar boulder fronts on a smaller scale occur at other localities on Parsley Bar.

The term "boulder front" is used here to indicate a scarp or face of boulder gravel normal to the flow direction. The deposits are not similar to the bouldery snouts of mudflows, to which the term has been applied, in that the entire deposit in this case is composed of boulder gravel.

Like the berms, the main boulder front apparently is characterized by presence of the coarsest clasts at the surface, although the coarseness of the deposit precluded thorough excavation. The front occurs in a rapidly expanding part of the Parsley Bar reach. During the flood recession, the front was incised at the position of the present low-water channel, and coarse material was moved a small distance downstream. The single cored boulder of dam fill observed beyond this point was probably transported by macroturbulence during the surge peak.

The front represents the point in the channel at which the critical tractive force fell below the value necessary to move the entire flow, because of reduction of depth associated with the gradual but pronounced

FIGURE 16.—Large gravel bar formed 1.2 miles below Hell Hole damsite. Riffle in foreground is parallel to stream course. Bed material is predominantly rockfill from the dam. Width of channel is approximately 200 feet.

expansion of the reach and reduction in slope. A stage measurement showed that maxium depth of water at this point in the channel was 5–6 feet above the top of the deposit and was probably substantially less at the time the boulder flow reached this point. Competency necessary to move the mass was clearly much less than that required to move the component particles individually.

Two alternative hypotheses for formation and movement of the boulder front are proposed. According to one, the boulder front represents the front of a type of subaqueous viscous flow in which the bedload moved as a churning mass—fluid, yet sufficiently viscous to move as a discrete unit. Fronts that are possibly in part analogous have been reported on subaerial gravelly mudflows by Sharp and Noble (1953, p. 551) and Fahnestock (1963, p. 20) and on flood gravels by Krumbein (1942, p. 1364) who applied the term "boulder jams." According to Krumbein, longitudinal segregation results in concentration fronts of very coarse debris which dam the channel.

Alternatively, the boulder fronts may represent a large wave of gravelly material analogous to a sand wave or delta front. Movement is by rolling and saltation of the component material at the surface of the deposit until the foreset part or avalanche face of the form is reached, whereupon particles cascade down the front and are at least temporarily deposited owing to the sharp reduction in competence at the crest of the front. Migration of the dune form or delta takes place continuously by erosion of the upstream surface and deposition on the front. Tractive force necessary is that required to move the component particles as normal bedload.

Dune or delta movement obviously requires particles with similar hydraulic behavior, and dune materials are thus generally fairly well sorted. Consideration of this mode of transport is based on two lines of evidence. The morphology of the front is remarkably similar to that of generally smaller scale sand waves or migrating microdeltas (Pettijohn and Potter, 1964, pl. 74). However, strongest evidence for this mode of formation is the presence of probable crossbedding of an amplitude similar to the height of the boulder front and exposed in a cutbank in glaciofluvial deposits of Pleistocene age at the same position in Parsley Bar.

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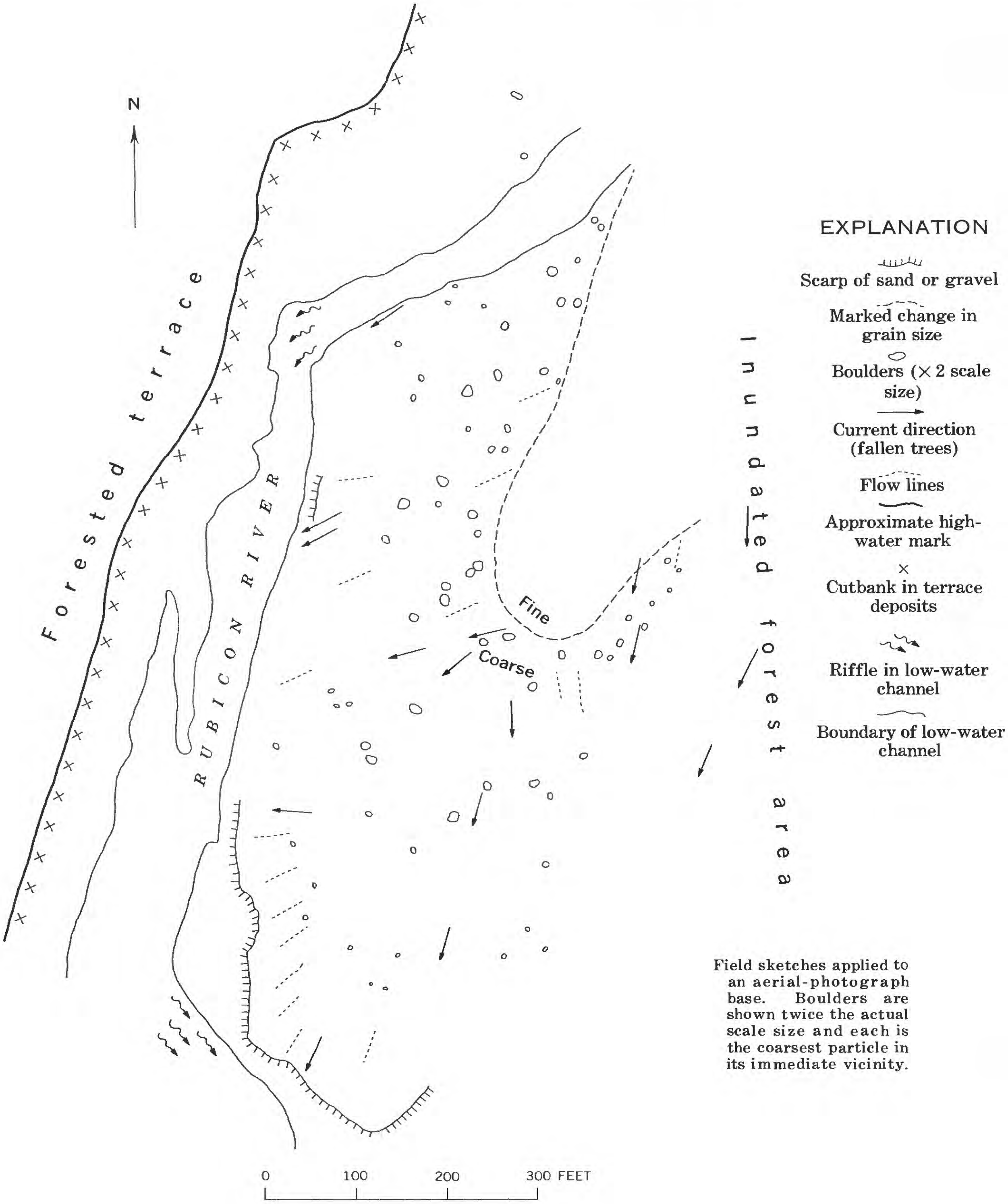

FIGURE 17.—Radial pattern of flow and deposition at the downstream end of Parsley Bar.

FIGURE 18.—View across flood channel of boulder front on Parsley Bar, Maximum height of the front is 7.2 feet. Note trees tilted in a downstream direction, to the right.

Crossbedding, inclined stratification in most places truncated at the upper surface, is preserved evidence of the migrating front or foreset area of dune or microdelta. Thus, wave movement with large amplitude probably occurred at that point on the bar during Pleistocene time. The crossbedded unit, which will be described below, contains a few clasts of boulder size but is dominantly a sand, pebble, and cobble gravel.

The material making up the boulder front deposit in the foreset region has a median diameter (74 mm) that is much in excess of any reported value for crossbedded deposits and sorting (σ_I=2.34; S_o=3.36) that is substantially poorer than any previously recorded for deposits whose texture has not been altered by induration. A surge released by failure of a natural gravel fill formed large dunes with a modal class of granules (2–4 mm) in the foreset region (Thiel, 1932, p. 456), but the resulting deposits were substantially better sorted than the boulder fronts on Parsley Bar. The Parsely Bar example contains some extremely coarse boulders with *diameters equal to the probable thickness of the deposit.* The authors conclude therefore, that the deposit and the boulder front primarily represent the sudden cessation of in-mass viscous flow of bed material. Movement of this type has not been directly observed, and its general importance in fluvial transport cannot be evaluated at present. This species of subfluvial debris flow can be considered transitional between mudflow and normal bedload movement by sliding, rolling, and saltation. The large-scale crossbedding and smaller, dunelike fronts composed of better sorted material indicate that local movement of material in the form of dunes in which the front represents an avalanche face probably accompanied the mass flow. Both forms of movement probably occurred simultaneously.

EPISODIC BOULDER MOVEMENT

A series of three berm surfaces 1 mile below the damsite shows that a series of boulder movements occurred during the surge. These surfaces are underlain by rockfill from the dam (fig. 20). Adjacent to the channel wall at this site is a very coarse deposit in which no lateral variation in size was noted. This deposit abuts against a distinctly finer bermlike mass characterized by a marked fine-to-coarse gradation toward the center of the channel. In the central channel the material is distinctly finer than in the adjacent berm, but is similarly coarser toward the channel axis. Thus, during

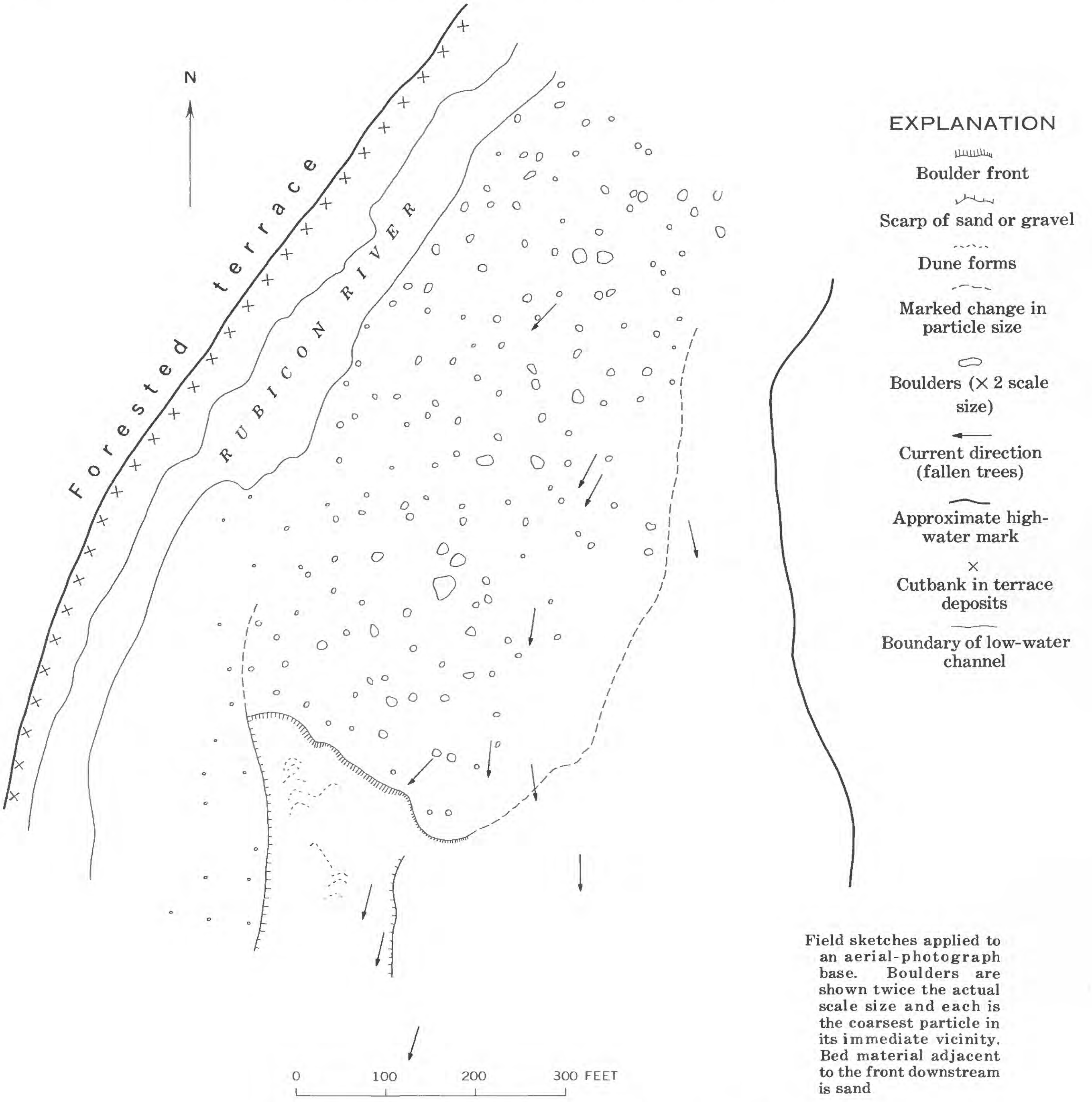

FIGURE 19.—Part of Parsley Bar containing the largest boulder front.

each of three episodes, successively finer materials were deposited, but within each deposit the grain size probably coarsened toward the center of the channel. The relative difference in particle size between berms and channel is thus partly explained. In the steep-walled confining reach nearest the dam and at the downstream terminus of rockfill movement, only a single episode of movement is preserved and is recorded by deposits in which the coarsest material is in the middle of the channel.

The sequence of berms noted in the dam-fill material and the boulder front on Parsley Bar both suggest that movement of bed material was episodic in response to a single flood wave. The possibly irregular supply of rockfill by periodic caving of the dam embankment may explain the berm sequence. According to an eyewitness, however, failure of the structure was gradual and continuous. Movement of bed material as viscous debris flows and dune forms created longitudinal concentrations of boulders moving down the channel. In any reach of channel other than Parsley Bar, the boulder

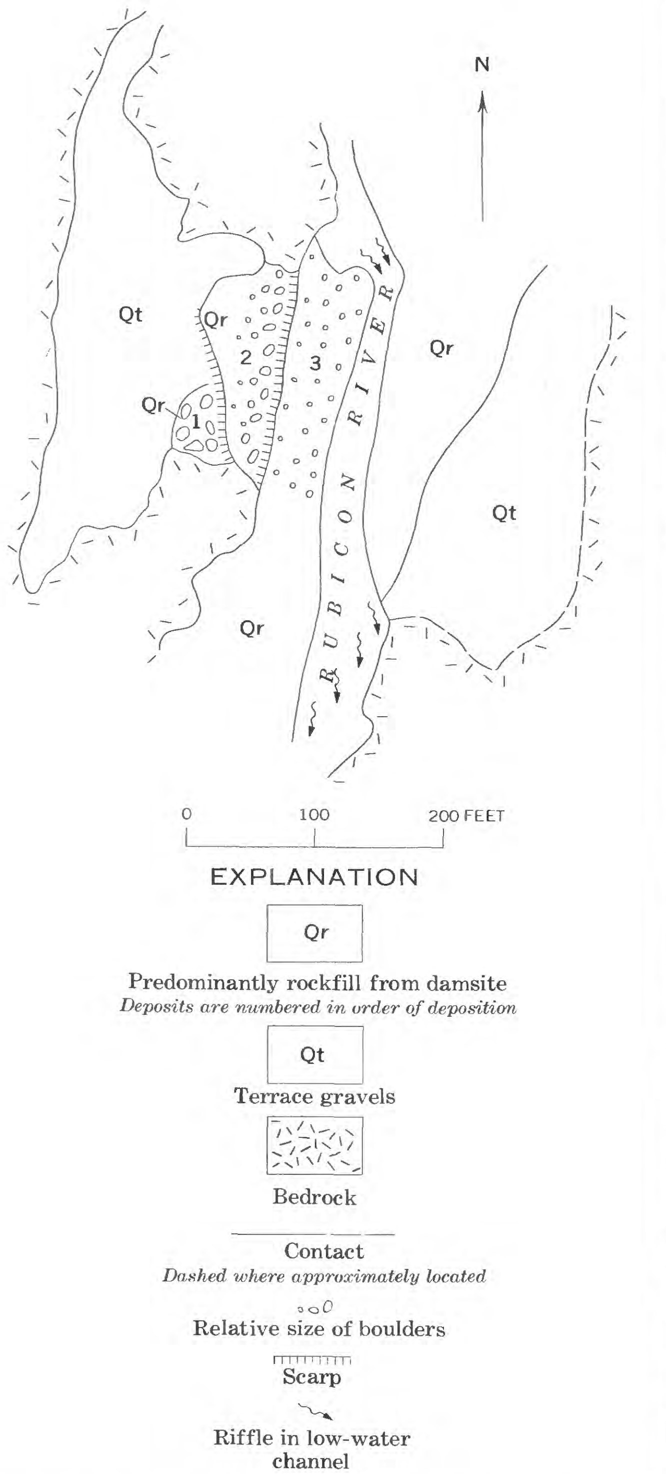

FIGURE 20.—Reach showing sequence of bedload movement. See figure 3 for location.

fronts would have migrated to a point where locally increased competence, at a channel bend or constriction, would have removed material from the flow or wave front at the same rate it was supplied, and coarse material would tend to accumulate and form a riffle analogous to a kinematic wave (Leopold and others, 1964, p. 212). Movement in waves or as viscous flows in response to extraordinary floods may be a factor in controlling the pool-riffle pattern in boulder-bed streams.

POOL AND RIFFLE PATTERN

Most stream channels show longitudinally alternating deeps and shallows, described as pools and riffles. Pools are the quiet stretches of relatively smooth water, and riffles occur in steeper parts of the channel with more rapid flow. Such sequences are scarce in the upper section of the Rubicon River above Parsley Bar, and the comparison of preflood and postflood aerial photographs shows that there are now fewer rapids in this upper, heavily aggraded part of the flood course than were there before the flood surge. In the sinuous section of channel immediately above Parsley Bar, the typical pool-riffle pattern is well developed. Riffles are located where the low-water flow moves across the bar and impinges against the bedrock wall of the channel. In general, the preflood pattern of pools and riffles has not been greatly changed. The preflood pattern of Parsley Bar has been modified and pool-riffle sequences are now few. Creation of a few new riffles resulted from supply of coarse detritus by terrace erosion during the receding stage of the surge and from cessation of movement of the boulder fronts.

The normal pattern of alternately pitching bars and pools and riffles predominates in the channel between Parsley Bar and the downstream end of the Rubicon River. Demonstrable modification of a pool and riffle has occurred at the site of the Rubicon River-Foresthill stream-gaging station where a riffle just downstream from the bridge at that location has been removed and is now the deepest part of a pool. The poor resolution of both sets of preflood aerial photographs in that part of the canyon prevents precise documentation of other changes in the pattern. Definite new riffles were formed by lateral supply from mass movements of material too large to be moved by the flood (fig. 21). The comparison of aerial photographs suggests, however, that there are now fewer riffles in that section of the surge channel. The flood removed numerous deltaic contributions of sediment by tributary streams and small preflood mass movements that had created riffles.

No noticeable modification of pools and riffles occurred on the Middle and North Forks of the American River, although a few minor changes in configuration

FIGURE 21.—Contribution of sediment to the flood channel by a landslide, 2.5 miles upstream from the junction of the Rubicon River with the Middle Fork American River. Because the slide occurred after passage of the surge at a stage during which the competence was insufficient to transport the coarses detritus of the slide, a riffle sequence was formed. Material with intermediate diameters in excess of 10 feet remains in the channel. Base of the slide is 535 feet across.

occurred. Mass movements directly resulting from the flood are also relatively minor along that part of the channel.

BED-MATERIAL FORMS AND INTERNAL SEDIMENTARY STRUCTURES

Deposits of the flood surge in the upper reaches are noticeably lacking in preserved sedimentary structures owing to the extreme coarseness of the deposits. Stratification could not be observed in the exposed berm sections. Surficial forms in the sand deposits consist of longitudinal ridges, flat-topped bars which in some places are associated with fronts as much as 2.5 feet high, and a series of crescentic convex-upstream waveforms as much as 20 feet across, visible on aerial photographs but not readily noticeable on the ground.

The fronts associated with the sandbars do not display internal stratification, either plane or crossbedded. Horizontal stratification, which is evidence of a plane-bed form, becomes abundant in the sand and gravel deposits of the lower reaches, particularly on the Middle and North Forks of the American River. Sand deposits of the lower reaches shown abundant crossbedding and ripple lamination, as well. Sets of crossbeds are tabular, with approximately parallel cutoffs and nontangential foresets, and have an amplitude of as much as 10 inches. Current-ripple lamination consists of climbing-ripple forms, as much as 0.8 inch in amplitude, of Walker's type 1 and 2 (Walker, 1963, p. 175) in cosets as much as 4 inches in thickness interbedded with plane-bedded strata. Abundance of preserved bed forms in a downstream direction in both gravel and sand deposits reflects a general decrease in grain size downstream and more sustained flow in the lower reaches. Lack of structures in the sand deposits of the upper reaches, such as Parsley Bar, may reflect rapid deposition. Plane beds, preserved as horizontal stratification, are usually interpreted (Gwinn, 1964, fig. 1) as evidence of the upper rapid-turbulent flow regime of Simons and Richardson (1961); dunes and ripples, preserved as types of crossbedding, as evidence of the lower, tranquil-turbulent flow regime.

The cutbanks of the glacial terrace deposits show a variety of crossbedding. Crossbedding with an amplitude of as much as 7 feet occurs in the deposits of Parsley Bar. The inclined strata of these largest crossbeds consist of highly variable layers of sandy pebble and cobble gravel and are at the base of the youngest unit of the alluvial stratigraphic succession (fig. 4). Trough crossbedding, preserved evidence of crescentic dunes, is abundant in the units of white sand and silt and rust-colored granule gravel occurring above the main body of till.

TRANSPORT AND DEPOSITION OF BED MATERIAL IN REACH DOWNSTREAM FROM DAMSITE

DOWNSTREAM CHANGES IN PATTERNS OF BARS AND BERMS

Berms of dam-fill diorite are present immediately below the dam; they grade downstream, at progressively lower elevations, into deposits in the present channel thalweg. The pattern of berms that sharply abut against valley walls is gradually replaced by a pattern of local flat-topped and lobate bars. The bars and the terrace-accretion deposits seem to have been molded of locally derived stream alluvium by the initial flood peak which had not entrained much coarse dam-fill material. There was a distinct time lag between formation of the lateral bars of stream alluvium and arrival of the bulk of the dam fill which predominates within the channel itself.

Upon reaching Parsley Bar, flow expanded from the confining bedrock channel, cut into terrace deposits, and formed boulder fronts and a large medial bar with radial flow patterns. Movement of the dam fill ended abruptly at the head of the bar, 1.6 miles below the damsite. The dam fill moved as a nearly undiluted mass because the surge had virtually cleared the channel. Beginning with the bedrock channel at the lower end of Parsley Bar, the normal pattern of alternately pitching gravel bars occurs.

COMPOSITION

The percentage of diorite in streambed materials is plotted against distance from the original toe of the dam in figure 22. The sharp contrast between the bed material in the reach above Parsley Bar and in Parsley Bar itself is evident from a comparison of figures 14 and 23. A large majority of the diorite boulders in the deposits which contain more than 90 percent diorite (fig. 14) originated from the dam embankment. Even at the downstream terminus of the in-mass movement of fill where only 8 percent of other rock types dilute the deposit, probably less than 6 percent is diorite derived from within the channel. This conclusion is based on the proportion of diorite to other rock types in the

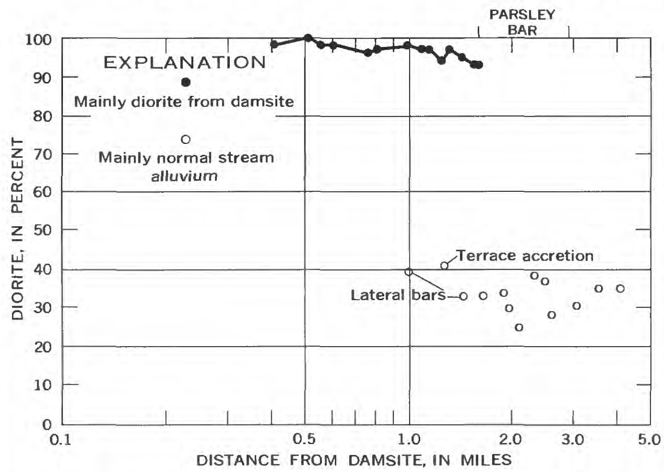

FIGURE 22.—Relation of bed-material composition, in terms of the percentage of diorite, to the channel distance downstream from the damsite. All measurements, except those noted, were made in or near the thalweg.

bars composed of locally derived material that were formed during an earlier stage of the surge. A small proportion of the diorite in those bars was derived from the dam fill, in all probability less than 10 percent.

PARTICLE SIZE

The size of particles moved by the flood was measured to obtain some idea of variation in dynamics along the stream channel and possible variations in competence in a downstream direction. The method described by Wolman (1954), in which the intermediate diameter of 100 clasts is measured in the field, was used because of the extreme coarseness of the deposits. A preliminary evaluation suggested that samples involving traverses perpendicular to the channel would show great variation. Therefore, a tape was used to construct a sampling grid in the area of each reach containing the coarsest particles.

Several sampling problems occur in measurement of bed materials as coarse as those present in the surge channel. In some samples the intermediate axis must be approximated, but placement in the correct size class for calculation of a size distribution is generally possible. Boulders having a diameter greater than −9 on the phi grade scale (512 mm) are difficult to maneuver into a position where the true intermediate axis can be measured. Where large boulders are partly buried, the exposed minimum diameter was used as an approximation of the intermediate diameter. When the grid point fell over a crevice in boulder gravels with an openwork texture, not even an approximation of the size of the selected particle was possible. Such sampling points were excluded.

FIGURE 23.—Bed material of Parsley Bar, extending from 1.6 to 2.9 miles downstream from the Hell Hole damsite. Very little rockfill moved this far. The material is predominantly reworked terrace gravel. Compare with figure 14. Weathered diorite, granodiorite, and granite are the main rock types.

Figure 24 is a plot of the graphic mean diameter (Folk, 1964, p. 44) at localities sampled in the upper reaches, calculated from the formula:

$$M_z=\frac{\phi_{16}+\phi_{50}+\phi_{84}}{3}$$

where subscripts represent the percentage of material larger. The median diameter of each sample is also included in table 3. Relative to the median, the graphic mean is a more valid measure of overall size of the sample and closely approximates the computed mean.

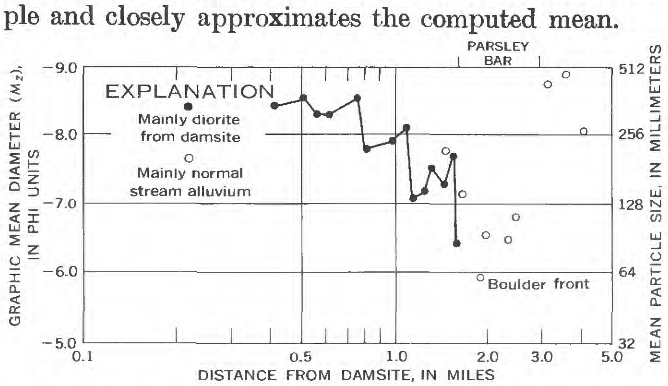

FIGURE 24.—Relation of mean particle size to distance downstream from damsite.

The size of the dam-fill detritus systematically decreases downstream. Additional measurements were obtained to compare the relative coarseness of sediment in several pool and riffle deposits (fig. 25). Each of the riffles contains coarser material than does the upstream pool. To determine change in particle size with depth, a pool deposit in a heavily aggraded part of the reach

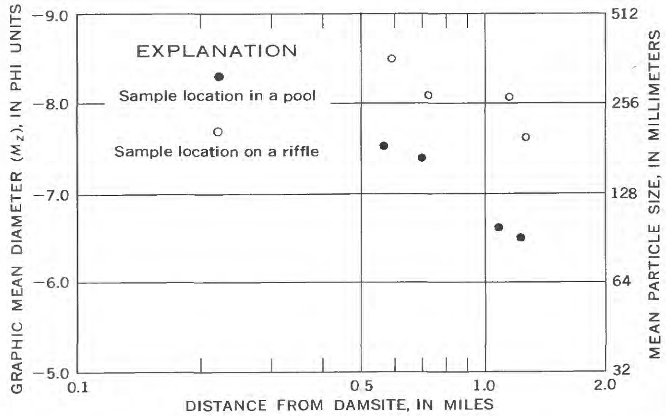

FIGURE 25.—Relation of mean particle size of samples in pools and riffles to distance downstream from damsite.

TABLE 3.—*Summary of sediment data in channel below damsite*

Sample	Distance from damsite (miles)	Median b-axis particle size (mm)	Graphic mean b-axis particle size M_Z	Trask sorting coefficient S_o	Phi standard deviation $\sigma\phi$	Inclusive graphic deviation σ_I	Phi skewness $a\phi$	Inclusive graphic skewness SK_I	Slope S (ft per ft)	Maximum stage (ft)	Tractive force[1] (lb per sq ft)
1	0.42	338	−8.40	1.79	1.40	1.49	0.0	0.08	0.0304	58.0	110.0
2	.51	338	−8.53	1.79	1.30	1.30	−.15	.06	.0289	63.3	114.1
3	.56	416	−8.30	2.06	1.70	1.91	.35	.41	.0283	47.6	84.1
4	.61	315	−8.27	1.74	1.15	1.28	.04	.11	.0281	44.0	77.1
5	.76	416	−8.57	1.86	1.30	1.23	.15	.18	.0214	31.1	41.5
6	.81	274	−7.80	2.07	1.75	2.08	.26	.33	.0208	35.5	46.1
7	.99	239	−7.93	1.98	1.45	1.57	−.03	.11	.0207	37.0	47.8
8	1.10	274	−8.13	1.56	.95	.96	−.05	−.03	.0175	40.3	44.0
9	1.16	147	−7.07	2.08	1.60	1.78	.13	.27	.0172	42.5	45.6
10	1.27	147	−7.17	1.47	1.20	1.15	.08	.13	.0169	43.0	45.4
11	1.32	208	−7.57	1.63	1.00	1.00	.20	.21	.0165	41.0	42.2
12	1.45	169	−7.30	2.14	1.75	1.71	.09	.13	.0158	37.2	36.7
13	1.48	239	−7.77	2.14	1.70	1.73	.12	.16	.0158	36.0	35.5
14	1.56	208	−7.70	1.57	.90	.95	.0	.08	.0125	30.5	23.8
15	1.60	89	−6.30	1.51	.95	.99	.16	.20	.0125	25.0	19.5
16	1.67	169	−7.17	2.22	2.05	2.22	.17	.27	.0121	22.5	17.0
17	1.90	74	−5.93	3.36	2.40	2.34	.17	.17	.0058	23.8	8.6
18	1.99	112	−6.60	2.73	2.00	2.03	.15	.18	.0062	22.7	8.8
19	2.32	119	−6.50	2.37	2.00	2.00	.30	.30	.0061	29.6	11.3
20	2.50	137	−6.83	2.37	1.90	1.89	.21	.19	.0068	25.3	10.7
21	3.10	512	−8.77	2.13	1.75	1.79	.40	.37	.0134	34.0	28.4
22	3.55	588	−8.93	2.07	1.70	1.74	.24	.24	.0080	47.6	23.8
23	4.10	388	−8.10	2.15	1.75	1.73	.43	.36	.0085	44.3	23.5
P_1	.56	194	−7.53	1.51	1.00	1.03	.10	.18			
R_1	.59	416	−8.50	1.51	1.00	1.06	.30	.27			
P_2	.70	208	−7.40	1.63	1.05	1.08	.43	.44			
R_2	.73	315	−8.13	1.68	1.15	1.11	.22	.21			
P_3	1.09	89	−6.67	1.87	1.30	1.20	−.31	−.29			
R_3	1.15	256	−8.07	1.95	1.35	1.38	−.09	−.01			
P_4	1.23	91	−6.50	1.57	1.00	1.02	.0	−.03			
R_4	1.27	194	−7.67	1.46	.90	.95	−.11	−.10			

[1] Assuming γ=62.4 lb per cu ft.

between the dam and Parsley Bar was excavated during a period of subsurface flow. Only a slight increase in coarseness was observed to a depth of 4 feet. Thus, the difference in grain size between the material in pools and that in riffles is probably not a surficial effect.

Downstream size decrease is also shown by the intermediate diameters of clasts marked by shothole coring (fig. 26) which positively identifies such boulders as being supplied to the surge at the damsite. The relative coarseness of the cored boulders and the size of the bed material confirms the interpretation that the bulk of the detritus in the channel downstream as far as Parsley Bar consists of dam fill. The sharp end to the tongue of dam fill at the head of Parsley Bar, the marked reduction in competence owing to slope and stage reduction at that point, and the apparent lack of dilution of Parsley Bar bed materials by dam fill all suggest that coarse fill was not transported beyond the head of the bar, 1.6 miles downstream from the dam. However, a definite boulder of fill, having an intermediate diameter of 1.4 feet and containing a shothole, was found near the middle of Parsley Bar, 2.1 miles from the damsite, and downstream from the boulder front. The boulder was probably one of a very few pieces of detritus transported that distance during conditions of maximum turbulence, with or shortly after the surge crest. The noticeable rounding of the specimen suggests that it was not rafted to this point by vegetation.

DISTRIBUTION OF PARTICLE SIZE

The distribution of particle size of clastic elements at each sampling locality is presented in table 3 in the form of a sorting coefficient S_o (Trask, 1932, p. 71), the phi or graphic standard deviation σ_ϕ (Inman, 1952, p. 130), and the inclusive graphic standard deviation σ_I (Folk, 1964, p. 45). The measures of dispersion or sorting are calculated as:

$$S_0=\sqrt{\frac{D_1}{D_3}};$$

$$\sigma_\phi=\tfrac{1}{2}(\phi_{84}-\phi_{16});$$

$$\sigma_I=\tfrac{1}{2}\sigma_\phi+\frac{1}{6.6}\phi_{95}-\phi_5.$$

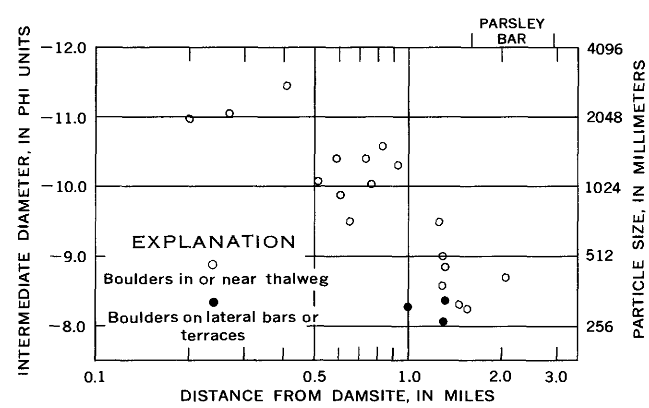

FIGURE 26.—Relation of diameter of larger cored boulders to distance downstream from damsite.

where D_1=diameter, in millimeters, at which 25 percent of the material is larger, and D_3=the diameter at which 75 percent is larger. Other subscripts also denote the percentages of material larger. For each of the measures, values are inversely proportional to the degree of perfection of sorting.

Figure 27 is a plot of the inclusive graphic standard deviation against distance downstream from the damsite. All the coarse deposits, regardless of location, can be characterized as poorly sorted relative to gravel found in most other geological environments, all values of σ_I being above 0.9. The degree of sorting is also on the low side relative to other published values of sorting of fluvial gravel (Emery, 1955, p. 47). However, an irregular increase in degree of sorting is evident in the dam fill distributed along the stream course. Material in the blasted fill was probably originally distributed according to Rosin's law, the geometrical relation between quantity of material in each size class produced by crushing. Some natural sediment sources, such as talus, glacial till, and mechanically and chemically weathered igneous rocks, approximate the distribution, in which each size interval contains about half the weight of material in the next larger interval (Krumbein and Tisdel, 1940, p. 301–304). Thus, the changes in size and sorting in the distributed dam fill should approximate the results of transportation away from a natural point source of sediment supply. The values should be only slightly affected by contamination as shown in figure 23.

Previous studies show that sorting commonly does not vary according to distance of transport when fairly short distances of transport are involved (Plumley, 1948, p. 548; Brush, 1961, p. 152). Normal stream gravel is the product of many probably short increments of movement accompanied by mixing with material in the channel, in-place weathering, and contributions from colluvium and tributaries. However, the effect on each individual supply of sediment, as shown in figure 28, is to increase the degree of sorting of the material as it is transported downstream.

Sorting is not, as would be expected, better in the riffles than in the pools. The beds of both pools and riffles composed of fill material are presently of openwork texture. Accumulation and infiltration of fines would be expected in the pools but not in the riffles, where velocity is greater, but infiltrated fines were not included by the surficial measurements.

Skewness, or degree of asymmetry of the distribution curve, was calculated as the phi skewness a_ϕ (Inman, 1952, p. 130) and the inclusive graphic skewness SK_I (Folk, 1964, p. 46), as follows:

$$a_\phi=\tfrac{1}{2}\,\frac{(\phi_{16}+\phi_{84})-\phi_{50}}{\sigma_\phi};$$

$$SK_I=\frac{\phi_{16}+\phi_{84}-2\phi_{50}}{2(\phi_{84}-\phi_{16})}+\frac{\phi_5+\phi_{95}-2\phi_{50}}{2(\phi_{95}-\phi_5)}.$$

Departure from 0.0 indicates the degree of asymmetry of the distribution, absolute limits ranging between +1.0 and −1.0. Most of the deposits are positively skewed, a characteristic of coarse fluvial gravel (table 3).

A plot of the inclusive graphic skewness (fig. 28) indicates approximate uniformity of skewness in a downstream direction. The apparent slight tendency for increase of positive skewness downstream may reflect only the fact that the deposits of normal stream gravel are more positively skewed than the deposits of fill material. No definable change in skewness resulted from sedimentation of the dam fill. The material in the fill was originally positively skewed if distributed according to Rosin's law.

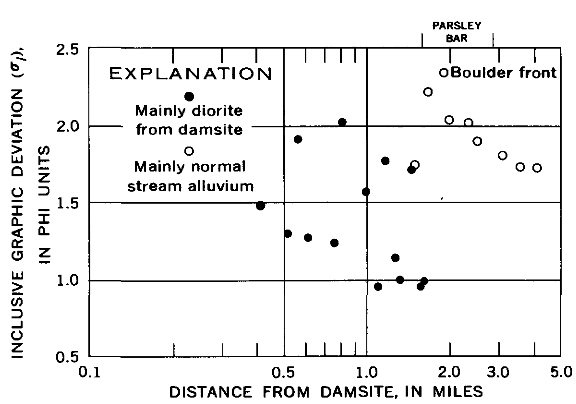

FIGURE 27.—Relation of dispersion in particle size to distance downstream from damsite. A decrease in the inclusive graphic deviation reflects increased sorting.

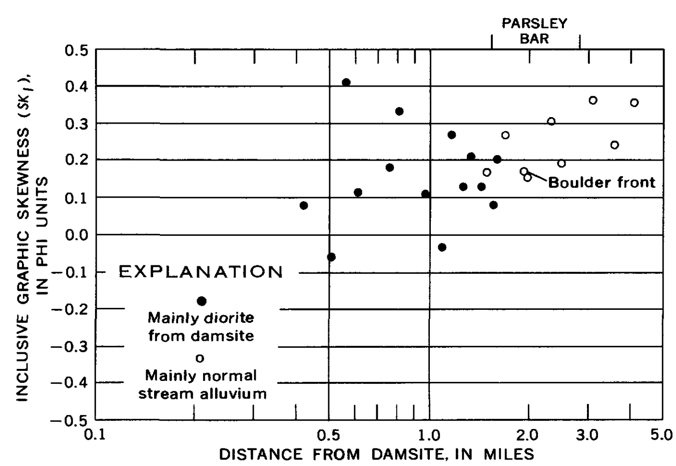

FIGURE 28.—Relation of skewness to distance downstream from damsite.

COMPETENCE

The transporting power or ability of moving water to transport debris may be expressed as competence, a measure of the maximum size of particles of a certain specific gravity that a current is able to move. Competence is commonly expressed in terms of the intermediate diameter of the largest particle that can be transported at a given flow velocity. Because of the likelihood of unstable flow and the laborious nature of indirect velocity determinations, which could have been made for only a few suitable reaches, tractive force was used as an alternative measure of competence (Leliavsky, 1955, chap. 5). Tractive force, $\tau=\gamma dS$, the "boundary shear" of fluid mechanics, is the product of the specific weight of the transporting medium, γ, water depth, d, and the slope of the hydraulic energy gradient, S, and represents the drag force per unit area of bed surface. Because the relation applies to uniform, steady flow and does not consider solid grain stress, it must be regarded as yielding an approximation of competence.

The slope of the energy gradient may be approximated by the slope of the channel surface which was measured on an enlarged part of a 7½-minute topographic map with 40-foot contours. Depth of flow was measured as the distance between thalweg elevation and high-water marks by level at previously defined cross-profile locations and by a hand level, mounted on a Jacob's staff, at other localities. Specific weight of the transporting medium, although doubtless variable, could only be treated as a constant.

A plot of changes in tractive force in a downstream direction (fig. 29) shows that variation was extreme. Flow was probably sufficiently competent throughout the course of the surge to transport boulder-size material in terms of the tractive force-particle size relations summarized by Fahnestock (1963, fig. 31). However, extrapolation of Fahnestock's data to the much coarser detritus of this study is certainly not warranted.

In spite of high competence, the fact that most large boulders were transported only short distances is shown by the striking predominance of locally derived rock types in boulder deposits along the lower unglaciated parts of the Rubicon and American Rivers. The small amount of longitudinal movement was due to the short duration of the surge, the extreme macroturbulence that rapidly moved debris to lateral areas of lowered velocity, and the fact that much erosion and supply of coarse material to the flood occurred after the flood crest. Study of the depositional forms clearly indicates that local sources of supply were a major factor in controlling particle diameter at a point.

In view of the large transport capability of the surge, an attempt was made to determine competency in terms of actual size of particle moved and to extend the rela-

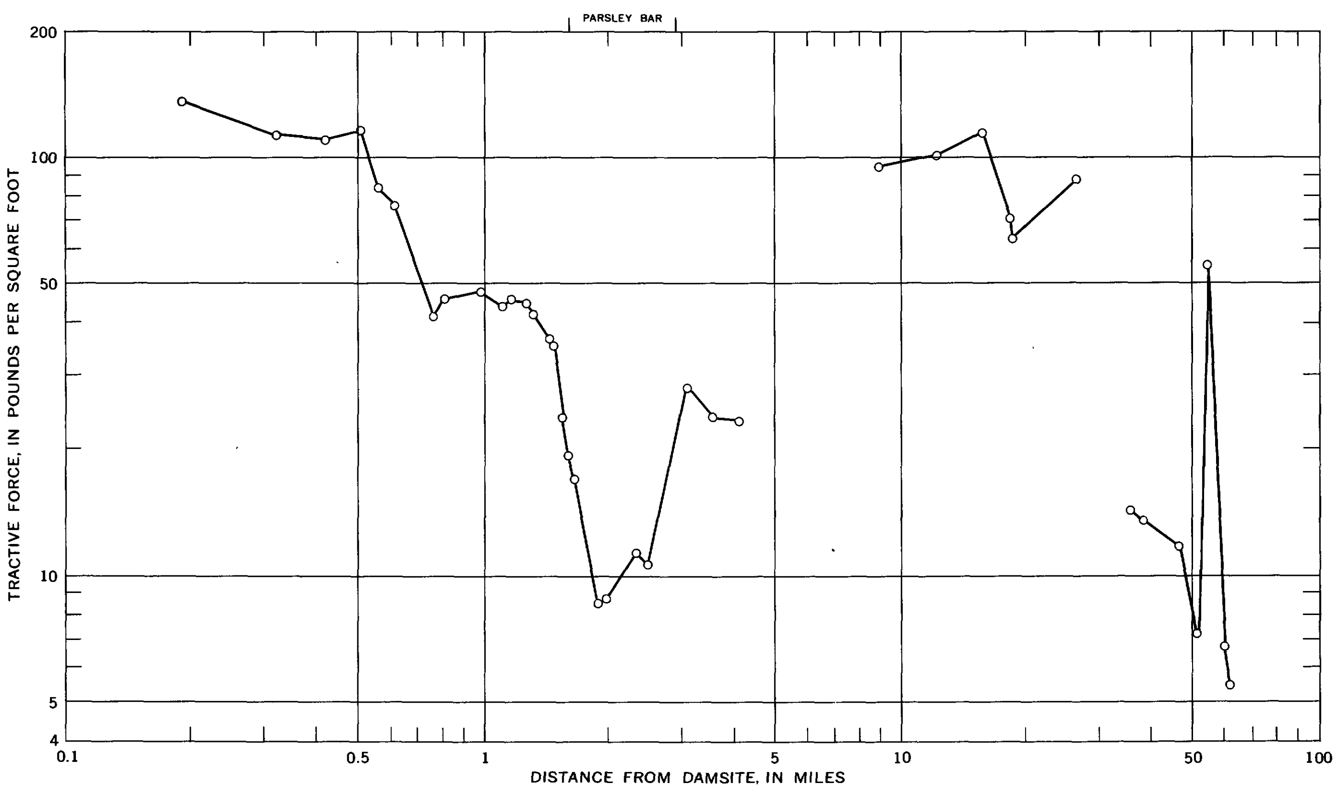

FIGURE 29.—Relation of indirectly measured tractive force to distance downstream from damsite.

tion between shear and size of particle moved. Particle size was measured on the assumption that all boulders on or only moderately buried in the bed had been moved by the flood. The following criteria were employed to indicate specific boulder movement: (1) Buried vegetation, (2) fresh abrasion on angular corners of downstream sides of blocks, and (3) presence in or on a depositional form clearly related to the flood wave, as indicated by buried or protruding vegetation and comparison of preflood and postflood aerial photographs.

Such an indirect approach is obviously uncertain, in part because we are dealing just with the exposed depositional remains of the flood detritus, which may be only a crude approximation of the actual maximum-particle transport past the sampling point. Furthermore, the velocity or tractive force permitting deposition of a particle should be less than that required to initiate or maintain movement. However, Kramer (1935, p. 824) found that under some circumstances deposition occurred at a higher value of tractive force than that at which movement began, because of roughness differences. In addition, rolling or a settling lag (Postma, 1961) may cause movement to continue into areas of substantially reduced tractive force.

The average intermediate diameter of the 10 largest particles at each of nine localities was measured to reduce the possibility that an unmoved boulder was included in the data. Measurements were restricted to the lower nonglaciated part of the channel, and only particles showing effects of abrasion were included. Angular blocks without abrasion and located near channel sides were attributed to purely lateral movement and were excluded. Data are summarized in table 4.

A plot of the mean intermediate diameter of the 10 largest particles against tractive force at each of the nine localities yielded a direct relation (fig. 30), similar to what would be expected in projecting the direct measurements of competence-size relations collected and summarized by Fahnestock (1963, fig. 31). Fahnestock's White River data are based on measurements of particles being transported and on shear calculated from mean depths; other data compiled by Fahnestock are based largely on particle erosion. The indirect method used in the present study, which utilizes depositional remains of a flow and maximum shear at the location of each particle, yields compatible results. Such an indirect determination of competence assumes that a spectrum of particle sizes up to and above the size which the flood is capable of moving is available.

Field relations are considerably more complicated than suggested by figure 30. There is great longitudinal variation in particle size, only in part related to the pool and rifle pattern, along a reach in which tractive

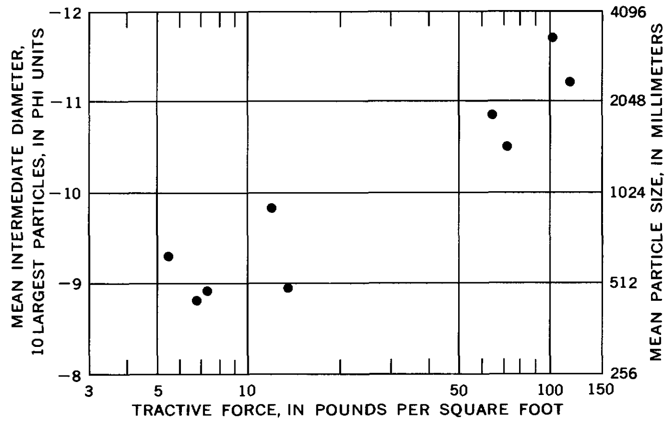

FIGURE 30.—Relation of maximum particle size to indirectly measured tractive force.

force must have been fairly constant. Measurements of maximum particle size and associated stage were made at localities that contained the coarsest particles in a given reach.

The extremely coarse material in the Rubicon gorge was clearly moved only very short distances. Additional evidence for small increments of transport of coarse material are particle-size changes at the point the flow left the plutonic terrain of the upper Rubicon and crossed the contact with metamorphic rocks of the Calaveras Formation. In the channel, just upstream from the contact, the average *b*-axis (intermediate axis) of the 10 largest granitic boulders measures 10.8 feet. In the metamorphic terrain 50–60 yards downstream, the 10 largest boulders of granitic composition average only 4.7 feet in diameter. The contract is below the maximum extent of glaciation.

ROUNDNESS

Downstream changes in particle shape were determined by application of Krumbein's visual comparison charts (1941a, pl. 1) to photographs of the bed material, as well as to individual particles observed in the field. Roundness is expressed as the ratio of the average radius

TABLE 4.—*Summary of maximum particle-size data*

Location	Distance downstream from dam (miles)	Mean *b*-axis particle diameter: mm	Mean *b*-axis particle diameter: Ft	Stage (ft)	Slope (ft per ft)	Tractive force (lb per sq ft)
Rubicon gorge; change in canyon configuration, plutonic-metamorphic contact	12.1	3,290	10.80	71.6	0.0226	101.0
Rubicon gorge	15.6	2,380	7.80	63.9	.0290	115.7
Rubicon gorge	18.2	1,450	4.74	64.1	.0179	71.6
Rubicon gorge; base of largest slide	18.5	1,830	6.00	61.1	.0169	64.5
Unnamed bar 3 miles below Middle Fork American River at Foresthill gaging station	38.5	497	1.63	56.2	.0039	13.7
Oregon Bar (upper)	47.2	899	2.95	53.1	.0036	11.9
Philadelphia Bar	50.7	479	1.57	45.0	.0026	7.3
Diversion dam	60.2	457	1.50	36.2	.0030	6.8
Oregon Bar (lower)	61.0	625	2.05	25.8	.0034	5.5

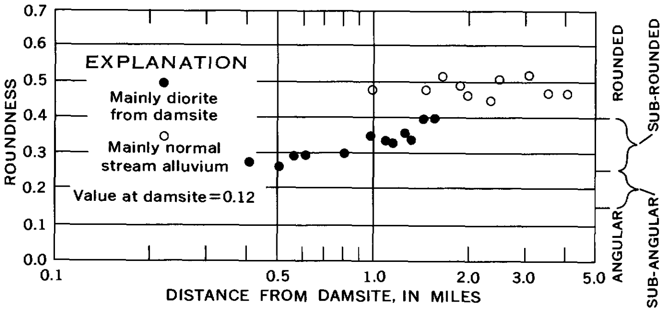

FIGURE 31.—Relation of particle roundness to distance downstream from damsite. Each value represents the average of at least 20 determinations. The range of values is much greater in the normal stream alluvium relative to the rockfill diorite.

of curvature of particle edges to the radius of curvature of the maximum inscribed sphere. Thus, roundness is theoretically independent of sphericity—the degree of approximation of the particle to a spherical shape—and is less sensitive to the internal structure of particles than sphericity. Changes in roundness are illustrated in figure 31, in which the average roundness of at least 20 particles is plotted for each locality.

Roundness of the rockfill particles increases rapidly downstream. Studies of roundness in streams and abrasions mills indicate that the rate of rounding decreases with distance and that roundness changes after a first small increment of transportation may be marked (Krumbein, 1941b, 1942, p. 1385; Plumley, 1948, p. 559). Experimental data indicate that rate of rounding may vary considerably with grain size.

The downstream grain-size decrease accompanying the rounding increase probably causes the apparent rate of rounding interpreted from figure 31 to be too low. Projection of the rate of rounding indicates that the dam fill would have obtained an average roundness corresponding to the roundness of the normal alluvial material in less than approximately 5 miles of downstream movement.

Roundness was also determined for the boulders containing shotholes (fig. 32) and the values are similar to those at the sampling localities, additional evidence that the bulk of diorite within the channel below the dam is

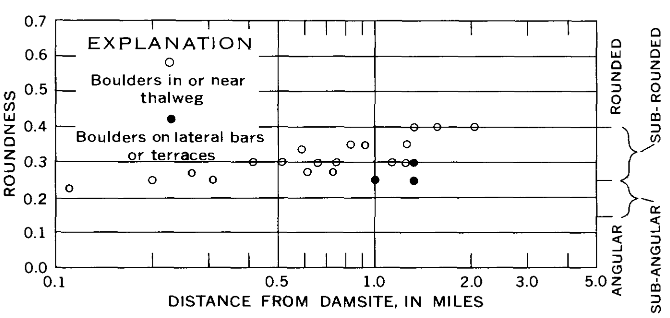

FIGURE 32.—Relation of roundness of cored boulders to distance downstream from damsite.

redistributed fill. Several cored boulders were discovered on and in the reworked alluvial and terrace gravel occurring as berms or bars along the main channel and as terrace accretions (fig. 11). Such boulders are perceptibly more angular than cored boulders within the central part of the channel. Distribution of the depositional forms and contacts between units indicates that the lateral bars, berms, and terrace accretions were formed earlier in the flood than the thalweg deposits. A lesser degree of rounding of boulders transpored during an earlier interval of the flood passage suggests that these boulders may have been carried in suspension by macroturbulence, or in part caught up and rafted by uprooted forest debris.

Roundness of the cored boulders indicates that transition from angular (0–0.15) to subangular (0.15–0.25) occurred almost immediately downstream from the damsite, using the roundness class limits of Pettijohn (1957, p. 59). Transition from subrounded (0.25–0.40) to rounded (above 0.40) in both cored boulders and bed-material samples occurred approximately 1.5 miles downstream.

In comparison with other geologic and experimental studies of rounding as related to time and distance, for comparable rock types, the greatest rounding per interval of distance transported was attained in this example. The greater particle size in this example is, of course, the major cause. Downstream dilution of the samples of dam fill by indigenous, previously rounded particles was assessed and did not influence the findings. The unusually rapid rounding occurred, however, in spite of the noteworthy uniformity and apparent durability of the freshly quarried diorite (fig. 6). An additional factor adding to the high rate of rounding probably is the intense turbulence and the resulting rigor of the transport environment. Schoklitsch (1933), for example, has shown that abrasion is intensified as velocity increases. Another factor is the possibility of bedload movement as subaqueous rock flows in which attrition by grinding could have been intense. As noted above, the deposits of rockfill from the damsite are openwork gravel in which the particles are dominantly boulders. The cushioning effect of fines was decidedly less than in normal bedload transport.

CAUSE OF DOWNSTREAM DECLINE IN PARTICLE SIZE

Most studies have emphasized abrasion as the fundamental cause of the often reported decline in size of fluvial sediment particles downstream. Experimental abrasion studies (Krumbein, 1941b; Kuenen, 1956) have shown that clasts become rapidly rounded under conditions simulating stream transport. The rate of rounding is, among other parameters, highly sensitive to particle size and composition, sorting, and position of a given particle within the distribution.

A second factor, progressive sorting, is difficult to assess, but is currently believed to be of at least moderate importance. Progressive sorting involves two aspects: (1) the lagging of larger particles, caused by the differences between particle velocity and flow velocity which are related to particle size under conditions of constant or increasing competency, and (2) the progressive deposition of the coarser grades during reduction in competency.

As previously shown, the bed material in the channel to a point 1.6 miles downstream from the dam originated at the damsite and has a known degree of dilution. Therefore, the effects of abrasion and progressive sorting can be evaluated. Over an interval of 1.2 miles, beginning at a point 0.4 mile downstream where rock recovery operations have not disturbed continuity of the deposits, the graphic mean size, in terms of intermediate diameter, changes from $\phi-8.0$ (256mm) to $\phi-6.5$ (91mm), a reduction of approximately 65 percent. Over the same interval, average rounding increases form 0.25 to 0.40. Krumbein's experimental results (1941b, fig. 3) show that limestone pebbles undergoing the same roundness change would be decreased in weight by only about 3 percent. Composition is not critical in extending these determinations to the diorite rockfill. In general, a fragment may become moderately well rounded without any appreciable effect on size and shape. Translation of weight decrease to the percentage decrease in particle diameter would be highly variable, depending on the individual particle configuration, but the intermediate-diameter change can be conservatively estimated as less than 5 percent. Therefore, more than 90 percent of the size decline is the result of progressive sorting. Plumley (1948, p. 570), using a different line of reasoning, concluded that 75 percent of the size decline in Black Hill terrace gravel was due to progressive sorting.

This determination pointedly neglects inclusion of a factor for size reduction by breakage. Thorough study of the rockfill deposits over their entire length revealed few broken rounds or fresh fracture surfaces. Consequently, breakage was not significant in the overall size decline, because of the tough, massive character of the fresh diorite. Smaller particles produced by flaking and chipping of coarser detritus were either carried past the area of fill deposition or infiltrated the openwork boulder deposits and did not appreciably influence the mean size of the downstream surficial samples.

Fracturing may be considerably more important in the big-picture view of fluvial sediments, however. According to Bretz (in Pettijohn, 1957, p. 537) broken rounds do not normally exceed 15 percent of a gravel deposit, but they may dominate, as in glacial-outwash gravel of the Snake River (Bretz, 1929). In view of the rarity of splitting in the rockfill boulders and its prevalence in older gravels, particle breakage may be chiefly due to in-place weathering along planes of weakness. The internal lithologic fabric of the particles is naturally an important consideration.

Figure 29 shows that size decline in the reach below the dam occurred under conditions of nearly continuously decreasing competency. However, when graphic mean size at each locality is plotted against tractive force (fig. 33), at best only a very crude association is evident. Such a relation emphasizes the importance of local channel configuration in controlling deposition and the longitudinal as well as lateral variation in particle size within the stream channel.

Although the downstream decrease in particle size of the bed material derived at the damsite clearly relates to progressive sorting and, in part, to a concomitant decrease in competence, the lagging of the larger particles because of fluctuations in flow competency is probably a significant cause of size decline on the Rubicon and Middle Fork American Rivers. Large fluctuations in maximum competency shown in figure 29 were present along the flood course, and similar changes in competency would occur for any flow in the canyon.

MACROTURBULENCE

The dynamics of the surge were such that turbulence was extreme, particularly in the reach below the dam where virtually no fines had yet been incorporated in the flow to dampen turbulence effects. Table 5 illustrates the effects of the turbulence as indicated by the diameter and height above the streambed of boulders deposited by the surge. Only boulders which were

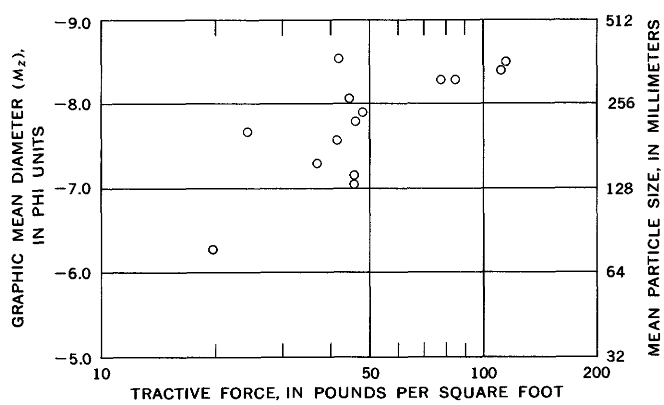

FIGURE 33.—Relation of mean particle size to indirectly measured tractive force.

freshly deposited were measured. There is a general decrease in magnitude of turbulent effects throughout the mile of channel below the dam. Below Parsley Bar, which was a source of a great quantity of fines to the flood, boulder movement did not occur much above the level of the channel bottom.

Matthes (1947) described forms of macroturbulence in streams, and emphasized the efficacy of spasmodic vortex actions which cause upward suction. Such phenomena, designated as kolks by Matthes, act in swift and deep water in a manner analogous to tornados in air, develop cavitation, and can lift bedload materials and pluck fragments from a jointed rock surface. Probably, such action was responsible for deposition of boulders well above the level of the channel and was effective in removal of some bedrock, particularly in reaches underlain by jointed granitic rocks.

EFFECTS OF THE SURGE RELATIVE TO NORMAL STREAM PROCESSES

Steep incised bedrock canyons of mountain rivers like the Rubicon may be blocked occasionally by massive landslips, the breaching of which could yield abrupt surges similar to that resulting from the embankment failure. The Rubicon River surge was more abrupt than most natural flood waves, and its effects would not expectedly duplicate those of ordinary floods. However, abrupt surges with unusually high discharges may be significant in rock-walled canyons along which damming by landslides or ice dams is a frequent geologic occurrence. The collapse of unstable ice dams probably produced many such surges in mountainous regions during the Pleistocene. Catastrophic floods, the jökulhlaups of Iceland (Thorarinsson, 1939), are also produced by the periodic glacier-damming of lakes, which are rapidly emptied when the impounded water buoys up the ice barrier.

Regardless of duration, catastrophically high flood peaks must greatly influence the morphology and sediment regimen in streams having extremely coarse bed material. The coarse detritus may be derived from glacial deposits, from gravity movements on valley sides, or by hydraulic plucking of joint blocks. The surge probably had a continuous maximum competency sufficient to transport large boulders for considerable distances; yet it did not, as indicated by tracing of material from the point source of sediment at the damsite, predominance of locally derived rock types, and size changes in a given rock type across a geologic contact. Difference between surge velocity and the slower velocity of tractionally moved particles caused entrained boulders to be soon stranded as they were bypassed by the surge peak. Lateral as well as longitudinal variations in competency were pronounced.

TABLE 5.—*Size and height above present thalweg and distance from point of origin of boulders deposited by macroturbulence*

b-axis particle-size		Height (ft)	Distance from damsite (miles)
mm	Ft		
1,550	5.1	28.0	0.07
396	1.3	35.0	.08
518	1.7	30.0	.17
1,158	3.8	34.0	.18
344	.8	41.0	.19
396	1.3	36.0	.20
213	.7	28.0	.31
183	.6	22.0	.37
683	.6	20.0	.41
274	.9	17.0	.42
518	1.7	33.0	.50
213	.7	40.0	.51
366	1.2	34.0	.51
683	.6	17.0	.57
213	.7	18.0	.85
305	1.0	15.0	.85

The usual annual floods are probably competent to move most materials in the nonglaciated parts of the canyon. Flows competent to move the coarsest material in the glaciated part of the canyon and the huge blocks supplied to the channel in the Rubicon gorge are probably so infrequent that decomposition, disintegration, and abrasion to a size transportable by unusual yet expectable floods outranks movement by catastrophic discharges in dispersal of the coarsest fraction. Many large blocks included in the till and terrace deposits of the upper reaches show deep weathering rinds.

The surge wave was probably at least the equal of the highest discharge attained in any part of the Rubicon River since glacial recession (within aproximately the last 10,000 years), as indicated by the erosional effects on glaciofluvial deposits in even the lower part of the river. The peak discharge of at least 300,000 cfs attributable to the surge compares with an estimated natural peak of about 40,000 cfs in the Hell Hole area.

Although not as important as a much greater number of annual floods in terms of volume of sediment transported and in denudation rates (Wolman and Miller, 1960), such catastrophic floods may control the morphology and character of depositional forms in mountain streams because of the extreme coarseness of the bed material. The surge passage totally modified and reestablished most depositional forms along the Rubicon River. This situation contrasts with alluvial channels in which both form and patterns are attributed to events of moderate frequency (Wolman and Miller, 1960, p. 67). The amount of actual landscape sculpture produced by catastrophic floods relative to normal stream processes, in both mountain and alluvial streams, is probably small.

One possibly unique aspect of such catastrophic events is the mass and wave movement of coarse bed material, such as occurred in the Parsley Bar reach.

Another effect of catastrophic floods may be the triggering of periods of increased mass movement by oversteepening of slope profiles. Tricart (1961) noted that a large flood in the French Alps activated a period of intensified soil creep and slumping. Such a cycle may have been initiated in the steep-walled yet thickly mantled Rubicon gorge. Observation of the flood route in April 1966 indicated that 38 new landslides, in addition to the 32 formed at the time of the surge, had occurred during the 1965–66 wet season, one of subnormal precipitation. The slides were generally smaller in size, having an aggregate volume probably less than that of the original slides. Soil creep not present the preceding year was evidenced by generally small areas of tilted trees adjacent to the flood channel. One large area of new slippage, 1,500 feet in length by 900 feet in height, was formed on the north side of Cock Robin Point, approximately 5 miles downstream from the gaging station, Middle Fork American River near Foresthill.

Another possibly unique effect of catastrophic surges is the supply of coarse sediment to the channel by lateral erosion of colluvium. However, the effects of erosion and apparent transportation of this single event indicate that the bulk of even coarse-sediment disposal may be accomplished by more frequent but less spectacular events in combination with in-place particle weathering.

SUMMARY AND CONCLUSIONS

1. The partly completed Hell Hole Dam failed on December 23, 1964, in response to a torrential 5-day rainfall of approximately 22 inches in the basin upstream from the damsite. Natural peak discharges in the region were generally equivalent to the maximum discharges attained in previous floods for which there is record, but the surge released at the damsite was greatly in excess of previously recorded flows along its entire route—61 miles of the Rubicon, Middle Fork American, and North Fork American Rivers. The flood surge was released over a period of 1 hour, during which the mean dischage was 260,000 cfs. Probable continuous attenuation in discharge occurred, and with the exception of the narrowing section of channel between Parsley Bar and the Rubicon gorge, reduction in height of the flood wave also occurred. Wave velocity averaged 22 feet per second.
2. Natural sources of sediment contributed to the flood included, in relative order of magnitude, stream alluvium, colluvium, glacial-outwash terrace gravel, landslides, glacial deposits, soil, and bedrock. More than 30 discrete landslides were triggered as a result of disturbance of slope equilibrium by scour along channel sides. Most of the mass movement occurred after the crest of the wave had passed, so large slides were not a significant source of sediment to the surge. Substantially more important as a source of sediment were the nearly continuous removal of colluvium by scour and flood-induced mass movements on a small scale.
3. A pronounced change in channel morphology occurred throughout the bedrock-controlled flood course, from a V-shaped channnel to one more broadly U-shaped. Erosion of channel sides was concomitant with thalweg aggradation, which was measured at five cross-profile sites and probably was nearly continuous along the flood course. Extensive aggradation in the 1.6 miles of channel below the damsite is related to deposition of rockfill from the breached dam embankment.
4. Depositional forms in the channel were strongly influenced by local sources of sediment. Terracelike berms were formed along channel walls in the reach below the dam, in which flow was highly macroturbulent, turbulence was not damped by included fines, and boulders were transported in suspension. As much as 5 feet of boulder gravel was added to the surface of a glacial-outwash terrace 28 feet above the presurge thalweg at a peak stage of 45 feet relative to the presurge thalweg.
5. Boulder fronts as much as 7 feet high and 250 feet long were formed transverse to flow direction in an expanding reach with a declining gradient. Such forms are interpreted as the snouts of discrete flows of bed material rather than waveforms, but wave movement also occurred. The evidence for movement of bed material as viscous subaqueous rockflows includes: (a) The presence of boulder fronts in the channel, (b) the presence in the deposits associated with the boulder fronts of extremely coarse particles with diameter equal to the thickness of the deposit, (c) the unusually poor sorting of the deposits, (d) the occurrence of the boulder-front deposits in reaches where the maximum tractive force applied by the surge did not approach the critical tractive force necessary to move the coarser individual particles. The terracelike boulder berms are believed to represent backwater deposition of bedload moved in this manner or by wave movement.
6. Some change in the pool-riffle pattern resulted from the surge passage, but because of the scale of all preflood aerial photographs, change could be documented at only one locality. New riffles were

formed by lateral supply of coarse material by slides and by cutting of boulder fronts, and some presurge riffles were removed.

7. The rockfill from the damsite moved as mass flows or as a series of waves without mixing in the channel thalweg, as far as 1.6 miles from the damsite, and a single boulder traveled 2.1 miles. Deposits above and lateral to the channel in this interval are attributed to an early phase of the surge, probably near the crest, and consist in large part of normal stream gravel and reworked terrace gravel. Compositional contrast between the two episodes of deposition from a single flood wave is pronounced.
8. Movement of the rockfill from the damsite demonstrated a pronounced downstream decline in mean diameter as well as an imperfect increase in degree of sorting. No regular change in skewness was detected.
9. The downstream decline in particle size occurred under conditions of continuously decreasing competency, as indicated by indirect measurements of tractive force. Sporadic measurements of tractive force along the rest of the flood route show that longitudinal variation in maximum competency was substantial. The competency of the flood was also determined by measuring the size of boulders moved. Maximum tractive force attained at a locality is related to the maximum size of boulders whose movement could be attributed to the flood, and the relation was compatible with previous studies of tractive force and particle size. With the exception of coarse material supplied laterally to the channel at a late stage in the surge when flow was not sufficiently competent to cause movement, virtually all detritus in the channel was moved. Distances traveled by individual boulders were small, however.
10. Rounding of the rockfill occurred more rapidly over a much smaller increment of transport than was anticipated from previous field and experimental studies; this unusual rate of rounding is explained by the coarseness of the material, the unusual rigor of the transport conditions, and the possibility of transport in subaqueous rock flow. Boulders carried in part in suspension at or near the surge peak and deposited on lateral bars are not as well rounded as those deposited in the thalweg. The massive diorite boulders were rounded after only 1.5 miles of downstream movement.
11. Consideration of the relative importance of abrasion and fracturing versus sorting effects indicates that progressive sorting is the dominant cause of the downstream decline in particle size of the rockfill.
12. If the effects of the surge passage are analogous to natural catastrophic floods, jökulhlaups, and those caused by the breaching of landslide dams, such floods, in mountain streams with bed material of boulder size, may set and control pool-riffle patterns, initiate periods of increased mass movement, and give rise to subaqueous mass flow in the channel. Another striking result of the surge was the introduction into the channel of large quantities of valleyside material, a major source of coarse material. Greater dispersal of the coarse sediment fraction is accomplished by normal floods in combination with size reduction by weathering than by natural catastrophe floods, however.

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INDEX

[Italic numbers indicate major references]

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GEOLOGICAL SURVEY

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CONTENTS

[Letters designate the separately published chapters]

O