Effects of the Catastrophic Flood of December 1966, North Rim Area, Eastern Grand Canyon, Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 980

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METRIC-ENGLISH EQUIVALENTS

Multiply English unit	*By*	*To obtain metric unit*
feet (ft)	0.3048	metres (m)
square feet (ft^2)	.0929	square metres (m^2)
miles (mi)	1.609	kilometres (km)
square miles (mi^2)	2.590	square kilometres (km^2)
acres	.4047	hectares (ha)
acre-feet (acre-ft)	.001233	cubic hectometres (hm^3)
gallons (gal)	.003785	cubic metres (m^3)
gallons (gal) / minute-foot (min-ft)	.01242	cubic metres (m^3) / minute-metre (min-m)
feet per second (ft/s)	.3048	metres per second (m/s)
cubic feet per second (ft^3/s)	.02832	cubic metres per second (m^3/s)
inches (in.)	25.4	millimetres (mm)
cubic feet per second per square mile (ft^3/s per mi^2)	.01093	cubic metres per second per square kilometre (m^3/s per km^2)

EFFECTS OF THE CATASTROPHIC FLOOD OF DECEMBER 1966, NORTH RIM AREA, EASTERN GRAND CANYON, ARIZONA

By M. E. Cooley, B. N. Aldridge, and R. C. Euler[1]

ABSTRACT

Precipitation from the unusual storm of December 1966 was concentrated on highlands in northern Arizona, southwestern Utah, southern Nevada, and south-central California and caused widely scattered major floods in the four States. In Arizona the largest amount of precipitation was in the north rim area of eastern Grand Canyon; about 14 inches (360 millimetres) was measured at the North Rim Entrance Station.

Evaluation of streamflow and flood-damage data from the Grand Canyon and the Kaibab Plateau indicates four distinct centers of high runoff; the largest area is along the south edge of the Kaibab Plateau and includes parts of Bright Angel, Clear, Lava, Kwagunt, and Nankoweap Creek basins. Although most of the precipitation fell on the Kaibab Plateau, most of the flood damage occurred below the plateau, where the runoff was concentrated in stream channels that carried flow from the high runoff areas to the Colorado River. The other areas of high runoff were (1) Modred, Merlin, and Gawain Abysses in Shinumo Creek basin, (2) near the North Rim Entrance Station, and (3) near the ridge known as Cocks Comb in North Canyon Wash and South Canyon basins.

All the flood damage to structures was in Bright Angel Creek basin. At Phantom Ranch and elsewhere in Bright Angel Canyon, the flood damaged a new pipeline and buildings that had not been affected by previous floods.

The largest amounts of streamflow occurred along Bright Angel Creek and the Milk Creek–Dragon Creek part of the Crystal Creek drainage basin. The most spectacular effects of the flood were along Milk Creek–Dragon Creek, where a mudflow caused extensive channel modification and obliterated a prehistoric—about A.D. 1100—Pueblo Indian mescal (cooking) pit. The flood event that occurred in the Crystal Creek basin has a recurrence interval of only once in several centuries. The flood in Nankoweap Creek may have been the largest that has taken place during historical times. Considerable flow and erosion took place along Clear Creek and damaged a prehistoric mescal pit. Near the mouth of Shinumo Creek, an old campsite that was occupied in the 1890's was not damaged; however, litter from the camp is present about 1 foot (0.3 metre) above the 1966 floodline.

The most catastrophic effects of the 1966 flood were caused by two mudflows that extended from the edge of the Kaibab Plateau along Dragon Creek in the Crystal Creek basin and Lava Creek in the Chuar Creek basin to the Colorado River. More than 10 other large mudflows occurred in Nankoweap, Kwagunt, Crystal, and Shinumo Creek basins; possibly one other large mudflow occurred in Bright Angel Creek basin. In addition, about 80 large debris slides left conspicuous scars in the amphitheaters at the heads of the side gorges, and at least 10 small slides occurred on the Kaibab Plateau within the Grand Canyon National Park. The storm was not the first to cause a mudflow since the beginning of the 20th century. An older mudflow, which may have occurred in 1961, is present along Tapeats Creek.

The streamflow that resulted from the December 1966 storm on the Kaibab Plateau caused considerable local scouring and deepening of channels, including some renewed arroyo cutting. Before the flood, nearly all channels were mantled by dense stands of grass, which retarded erosion. The 1966 floodflow reopened old scours and formed new ones. The amount of scouring was roughly proportional to the maximum depth of the flow. Renewed arroyo cutting occurred mainly along parts of Walhalla Glades and Outlet Canyon.

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INTRODUCTION

Precipitation during the unusual storm of December 1966 was concentrated on highlands in northern Arizona, southwestern Utah, southern Nevada, and south-central California and caused widely scattered major floods in the four States. In Arizona the largest amount of precipitation was in the north rim area of eastern Grand Canyon (fig. 1; pl. 1). Severe channel erosion accompanied the floods in Grand Canyon and damaged archeological sites dated A.D. 1050–1150 and modern facilities in Bright Angel Canyon. The most spectacular effects of the storm, however, were the mudflows and debris slides that occurred mainly in the amphitheaters at the heads of the gorges along the north rim. Mudflows in the Crystal and Chuar Creek drainage basins transported detritus from the north rim to the Colorado River. In many drainage basins the mudflows—the first documented in modern times in the Grand Canyon—and the extensive channel erosion indicate that the storm of December 1966 was a rare event.

In 1967 a series of reconnaissance surveys was made to determine the amount of flood damage and the areal extent of the storm of December 1966 and the amount of channel modification resulting from this and earlier floods. In the Kaibab and Walhalla Plateaus and the platform between Marble Canyon and Kaibab Plateau, drainage areas were inspected where accessible by roads. An aerial reconnaissance was made of the western slopes of Marble Canyon and the north slopes of Grand Canyon from Saddle Canyon on the east to Deer Creek on the west; along the tributaries of the Colorado River, selected sites were investigated in detail

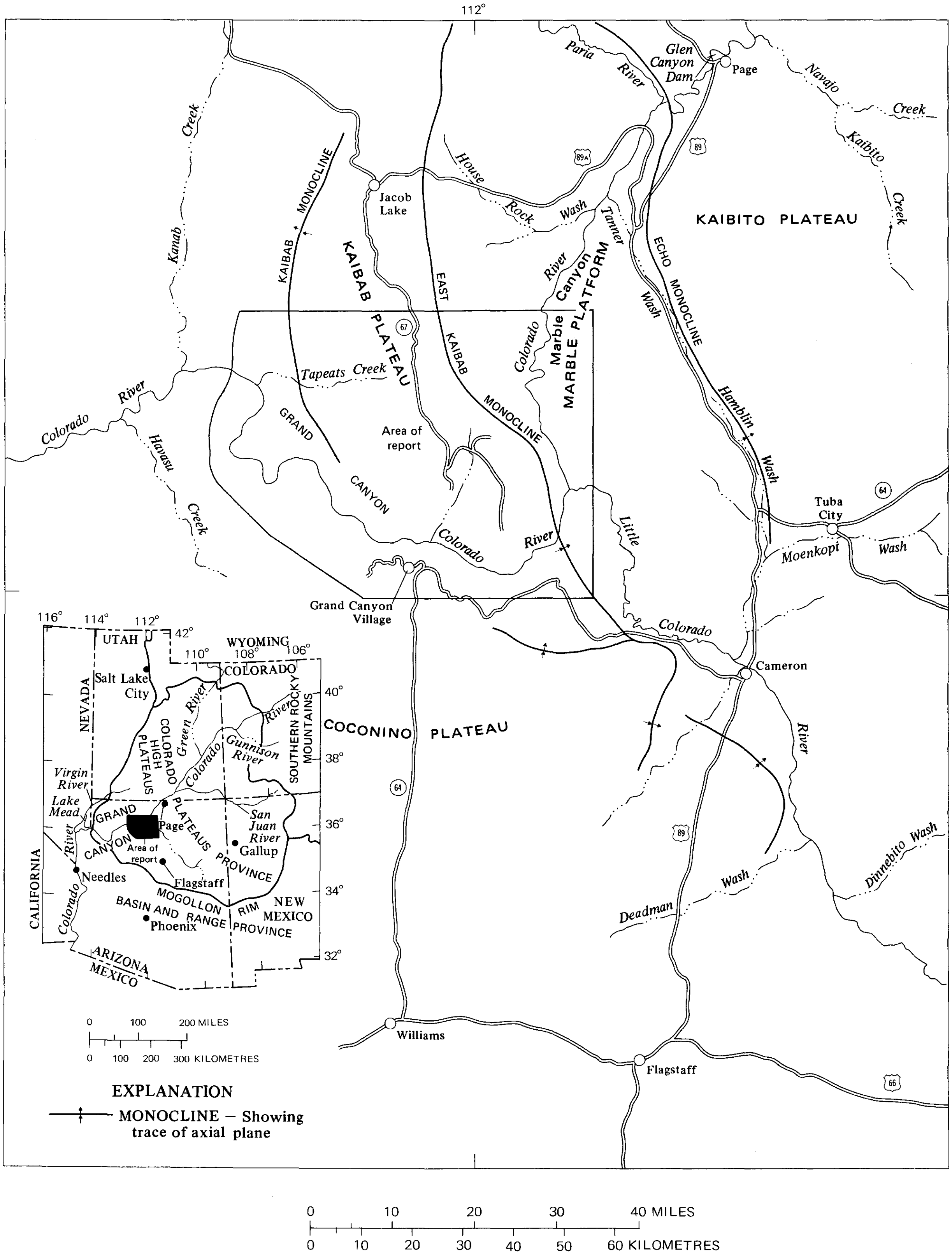


FIGURE 1.—Eastern Grand Canyon area and area of report.

on the ground, and indirect discharge measurements were made at a few of the sites.

PURPOSE OF THE INVESTIGATION AND SCOPE OF THE REPORT

The purpose of this investigation was to reconstruct the components of the flood of December 1966 in eastern Grand Canyon as indicated by field evidence and to obtain the information necessary to document an extreme hydrologic event in a semiarid environment. Although there is evidence of previous mudflows in eastern Grand Canyon, no documentation of the phenomenon exists in the literature on hydrology or geomorphology in Arizona.

This report describes the distribution and magnitude of precipitation, streamflow, and channel modification that resulted from the storm of December 1966 and documents the mudflows that resulted from the flood. The report relates the effects of the flood to those of previous known floods and to the prehistoric and historic occupation of the Grand Canyon.

REPORTING OF DATA

The U.S. Geological Survey has adopted the policy of reporting data in metric units in combination with English units. For this report, metric units are given in parentheses following English units in the text, and English and metric units are shown on the illustrations. The data in the tables are given in English units only.

ACKNOWLEDGMENTS

The authors are grateful for the storm-damage information contributed by H. B. Stricklin, former superintendent of the Grand Canyon National Park, and other National Park Service personnel. The authors also are grateful to G. L. Beck and P. W. Huntoon, geologists, who furnished many spring locations, and to G. L. Beck who furnished photographs of the flooded area for study. Substantial assistance, especially in the location of mudflows during flights, was given by Wayne Learn and Norman Browning of Tusayan Helicopters. R. C. Euler gratefully acknowledges the support of the National Science Foundation (Grant GS–1078) in his Grand Canyon archeological project, of which the present study came to be an unexpected yet valuable part.

PHYSIOGRAPHIC SETTING

The eastern Grand Canyon area is in the southwestern part of the Colorado Plateaus physiographic province in Arizona (fig. 1). The area consists of the Grand Canyon, its northeast extension Marble Canyon, and the tributary Little Colorado River Gorge (pl. 1). These physiographic features form a canyon system that is excavated to a maximum depth of about 1 mi (1.6 km) below huge rock terraces called plateaus and platforms. The highest terrace is the Kaibab Plateau, which borders the north rim of the Grand Canyon; the altitude of the plateau generally ranges from 7,000–9,000 ft (2,100–2,700 m) above mean sea level. The Coconino Plateau is south of the Grand Canyon, has a gently sloping surface, and is at altitudes of 6,400–7,200 ft (1,950–2,190 m). Marble Platform borders the Little Colorado River Gorge on the north and Marble Canyon on the east; the altitude of Marble Platform ranges from 5,400–6,100 ft (1,650–1,860 m) above mean sea level. A similar but smaller platform is present between Marble Gorge and the Kaibab Plateau.

Below the surrounding rock terraces, the Colorado River descends from about 2,870 ft (875 m) at Vaseys Paradise, to 2,700 ft (823 m) at the mouth of the Little Colorado River Gorge, to 1,930 ft (588 m) at the mouth of Deer Creek—a distance of 104 river miles (167 km). Tributaries to the Colorado River occupy side gorges that head into the north and south rims of the Grand Canyon, where gigantic amphitheaters have been carved (fig. 2). The floors of the amphitheaters are 2,000–3,000 ft (600–900 m) below the adjacent canyon rims. The gorges of the large drainage areas, such as Nankoweap and Bright Angel Creeks, slope rather uniformly from the amphitheaters to the Colorado River.

The eastern Grand Canyon area is characterized by a wide range in climate—from semiarid in the canyon to relatively humid on the Kaibab and Coconino Plateaus. The canyon cuts across an extensive orographic barrier that extends northwestward from west-central New Mexico along the Mogollon Rim and Coconino and Kaibab Plateaus to the high plateaus of southern Utah (fig. 1). In the eastern Grand Canyon area the amount of precipitation increases with increasing altitude owing to the orographic effect exerted by the Kaibab Plateau; storms tend to be concentrated on the windward southern part of the plateau between Pleasant Valley and the north rim of the Grand Canyon (pl. 1). This part of the area includes the crest of the Kaibab Plateau, and precipitation probably is between 25 and 30 in. (640 and 760 mm) per year. During 1931–60, the mean annual precipitation at the Grand Canyon National Park station on the south rim, which is at an altitude of 6,890 ft (2,100 m), was 14.77 in. (375.2 mm). (See U.S. Weather Bureau, issued annually.)

The classical Grand Canyon section includes Precambrian basement and sedimentary rocks and Paleozoic strata; the Paleozoic strata include the Tapeats Sandstone at the base and the Kaibab Limestone that forms the rim of the canyon (pl. 1). The Paleozoic strata are superbly displayed in the eastern Grand Canyon area, where the rocks outline a series of vertical-faced benches of resistant sandstone, limestone, or talus-strewn slopes that are on shaly rocks set back at different levels between the Colorado River and the enclosing rock terraces. The entire Paleozoic section is exposed throughout the area and ranges in thickness from about 3,500 ft (1,070 m) at the mouth of the Little Colorado River to 4,000 ft (1,220 m) near Shinumo Creek.

The escarpments in Grand Canyon present a favorable environment for the thawing and freezing action that accelerates mechanical weathering of rocks. Seepage from melting snow furnishes much of the moisture for the frost-wedging action along the canyon rims. The frost action is aided by the highly fractured nature of the rocks, which allows large blocks of rock to fall easily from the cliffs and accumulate as talus on the lower slopes or in the stream channels in the subjacent gorges.

HYDROLOGY OF THE FLOOD OF DECEMBER 1966

The storm that caused the unusual flood of December 1966 in Grand Canyon was the southeastern extension of a regional storm that started December 3 and lasted through December 7. The storm moved northeastward from the Pacific Ocean across the southwestern United States. The large amounts of precipitation caused major floods in the mountainous areas of south-central California (Dean, 1971), in southwestern Utah (Butler and Mundorff, 1970), and in parts of southern Nevada and north-central and central Arizona (Aldridge, 1971).

PRECIPITATION

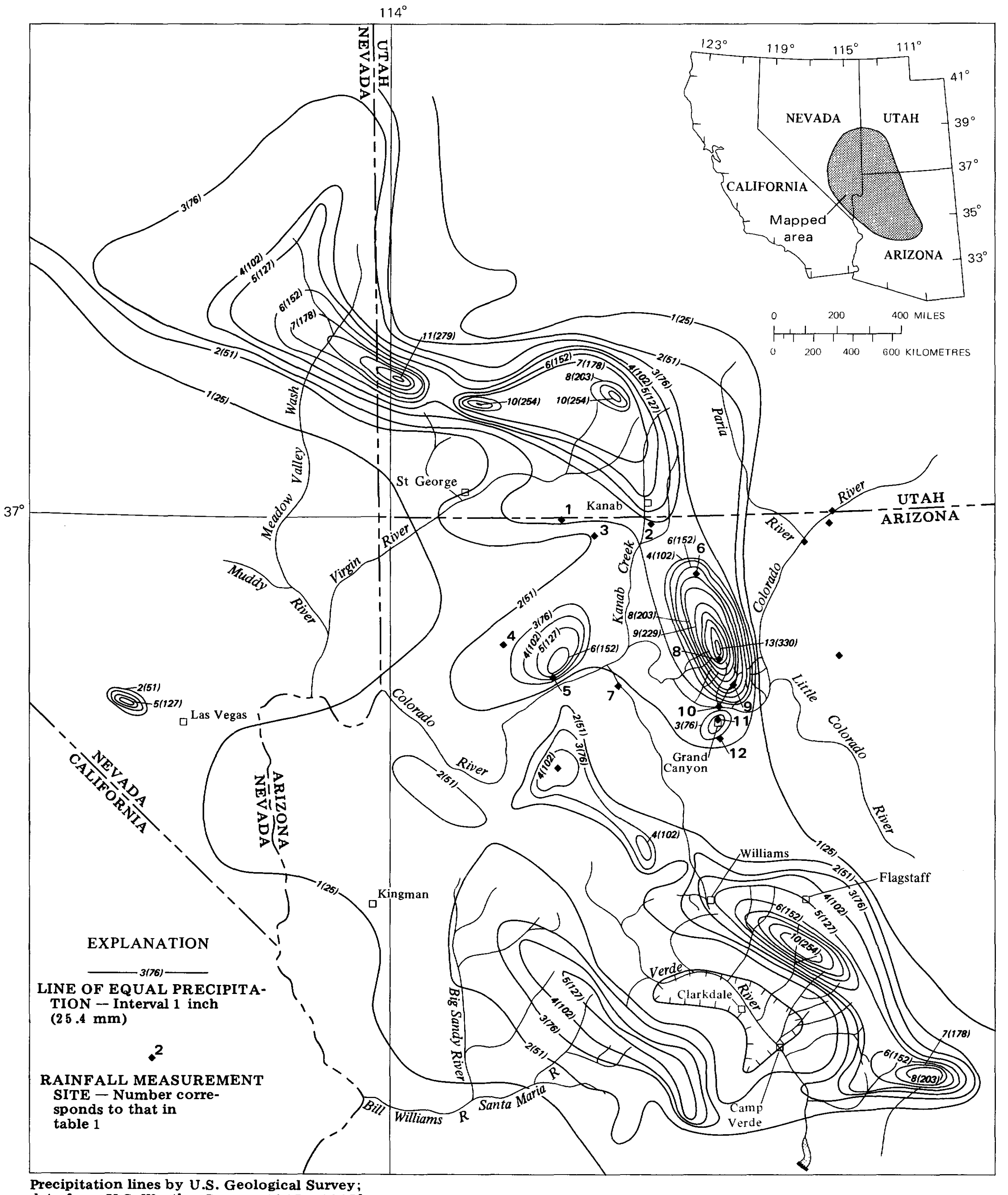
Few rainfall data are available for the eastern Grand Canyon area during or immediately preceding the storm of December 1966, because the precipitation gages had been converted to storage gages for the winter at Bright Angel Ranger Station and North Rim Entrance Station—the only stations in the area that had large amounts of precipitation. The precipitation stations along the south rim are not within the area of intense precipitation, which centered along the north rim and the crest of the Kaibab Plateau (fig. 2).

From November 1 to December 7, 17 in. (430 mm) of precipitation fell at the North Rim Entrance Station (table 1). National Park Service personnel estimate that a maximum of 3 in. (80 mm) was from November storms and that at least 14 in. (360 mm) was from the December storm. The gage at the Bright Angel Ranger Station was not read between October 1966 and May 1967; however, in the period between readings, this gage caught 83 percent of the amount caught at the North Rim Entrance Station in the same period. Applying the same percentage to the storm of December 1966, 11 or 12 in. (280 or 300 mm) probably fell at the Bright Angel Ranger Station.

During the storm of December 1966, the operating recording precipitation station closest to the eastern Grand Canyon area was at Tuweep, Ariz., west of the Kaibab Plateau. Precipitation started shortly after 0100 hours on December 3 and continued until 2100 hours (U.S. Weather Bureau, 1967a); it resumed about 1800 hours on December 4 and, except for about 3 hours, continued until 0400 hours on December 7. The times of rainfall at the Tuweep station, however, may not correspond with those in the eastern Grand Canyon area, as indicated by radar-echo maps of storm cells during December 3–6, 1966 (Butler and Mundorff, 1970, pl. 2). The maps show only a few small storm cells over the eastern Grand Canyon area, and they were present at times different from those over Tuweep. The cells appear to have remained over the eastern Grand Canyon area for very short periods; the time, location, and description of the cells are given in the following tabulation.

Time (hours)	Day	Description
0735	December 3	Two cells: One extended from about the North Rim Entrance Station eastward across the Kaibab Plateau to the headwaters of Saddle Canyon, and the other was over the southeastern tip of Walhalla Plateau.
1735	December 3	One very small cell near the Bright Angel Ranger Station.
0615	December 5	One long narrow cell that extended from the Bright Angel Ranger Station to the Utah border.
0735	December 5	Between 0615 and 0735 hours, the cell over the Bright Angel Ranger Station-Utah border area moved northward, and another cell moved in over the headwaters of Bright Angel Creek.
0935	December 5	One small cell near Cocks Comb at the head of North and South Canyons.
1735	December 5	One very small cell over the north rim.
1135	December 6	One small cell over Powell Plateau.
0800	December 6	No cells in the eastern Grand Canyon area.
0935	December 6	No cells in the eastern Grand Canyon area.

Radar-echo data are not available between 1735 hours on December 5 and 0800 hours on December 6 (Elmer Butler, oral commun., 1968), the period of most rapid rise in stage at the Bright Angel Creek gaging



Precipitation lines by U.S. Geological Survey; data from U.S. Weather Bureau, 1967a; 1967b; and Butler and Mundorff, 1970

0 50 100 MILES

0 50 100 150 KILOMETRES

FIGURE 2.—Location of precipitation stations near the Grand Canyon and precipitation data for December 3–7 in parts of northwestern Arizona, southwestern Utah, and southern Nevada.

TABLE 1.—*Precipitation at selected stations near the Grand Canyon, December 3–7, 1966*
[T, trace. Data from U.S. Weather Bureau (1967a)]

Rainfall measurement site (located in fig. 2)	Station	Altitude (feet above mean sea level)	Time of observation	Precipitation, in inches					
				Dec. 3	Dec. 4	Dec. 5	Dec. 6	Dec. 7	Total
1	Colorado City	5,010	Sunset	0	0.51	1.01	1.66	0.27	3.45
2	Fredonia	4,675	Sunset	.88	.10	.97	.92	.40	3.27
3	Pipe Springs National Monument	4,920	Sunset	.61	.10	.56	.21	.54	2.02
4	Mount Trumball	5,560	1900	.35	.33	(1)	1.50	.75	2.93
5	Tuweep	4,775	2400	.77	.24	1.39	3.57	.08	6.05
6	Jacob Lake	7,920	1800	(1)	(1)	(1)	6.60	0	6.60
7	Supai	3,205	1700	.40	.33	.11	.15	.59	1.58
8	North Rim Entrance Station	8,780	----	----	----	----	----	----	[2]14
9	Bright Angel Ranger Station	8,400	----	----	----	----	----	----	[3]12
10	Phantom Ranch	2,570	----	.04	1.02	.36	.32	.34	2.08
11	Grand Canyon National Park	6,965	1700	.30	1.15	1.69	1.01	.50	4.65
12	Grand Canyon Airway	6,971	2400	1.08	.42	1.60	.56	.33	3.99
13	Frazier Well	6,500	----	----	----	----	----	----	[4]5
14	Page	4,270	2400	.23	.01	0	.33	.12	.69
15	Wahweap	3,728	1700	.24	.08	.01	0	0	.33
16	Lees Ferry	3,210	Sunset	.12	T	.02	.17	.45	.76
17	Cedar Ridge Trading Post	5,920	1800	.37	T	T	0	0	.37

[1]Included with next reading.
[2]November 1 to December 7, 17 in.; October 1966 to May 1967, 25.6 in.
[3]October 1966 to May 1967, 21.2 in.
[4]November 1 to January 3, 6.05 in.

station. Therefore, it appears that the period of most intense rainfall—at least in Bright Angel Creek basin—was not covered by radar-echo maps. The determination of flood times along ungaged and uninhabited drainages cannot be pinpointed closer than during December 5–7.

At the time of the storm, the estimated snow depth was less than half a foot along the north rim of the eastern Grand Canyon, zero at the precipitation station at Grand Canyon National Park on the south rim, and zero at Jacob Lake. Only a trace of snow fell at the Grand Canyon station during the storm. It can be inferred from weather records that the soil probably was moist but not saturated. The last large amount of precipitation preceding the storm fell as snow on November 8–9. Only a few hundredths of an inch of precipitation fell between November 9 and December 3. Daytime temperatures were sufficiently high to cause melting of any snow but not sufficiently high to cause rapid melting, which would saturate the soil.

FLOOD AREAS

An evaluation of streamflow and flood-damage data for the Grand Canyon and the Kaibab Plateau indicates four distinct areas of high runoff (pl. 1). The largest area is a 5–7-mi-wide (8–11-km-wide) band along the southern edge of the Kaibab Plateau. The area extends from the headwaters of Crystal Creek basin eastward along the north rim to the headwaters of Nankoweap Creek basin and includes the upper parts of Bright Angel, Clear, Lava, and Kwagunt basins. Although this area had the largest floodflow, the amount was not uniform throughout the area. The drainages in upper Outlet and Fuller Canyons in the Bright Angel Creek basin had high peak discharges, whereas little flow occurred along the main stems of upper Bright Angel Creek and Crystal Creek upstream from the edge of the Kaibab Plateau (table 2).

The other three areas that had high runoff are (1) Modred, Merlin, and Gawain Abysses in Shinumo Creek basin, (2) near the North Rim Entrance Station where the Shinumo Creek, Bright Angel Creek, and North Canyon Wash basins join, and (3) near the Cocks Comb in the North Canyon Wash and South Canyon basins. In the area around the North Rim Entrance Station, high runoff is manifested by the road damage and by evidence of flow in all the channels that drain the area. The area flooded probably was quite small—an estimated 14 mi² (36 km²)—and little runoff reached the rim of the Kaibab Plateau or contributed to the flow in the area below the plateau.

Aerial inspection of Unkar, Vishnu, and Saddle Creeks and the many minor tributaries to the Colorado River that head below the rim showed little evidence of flood damage. Little evidence of flow was found in the stream channels in and adjacent to the Coconino Plateau south of the Colorado River.

MAGNITUDE OF FLOODS

The unit runoff—the amount of runoff per square mile—that occurred during the flood of December 1966 is relatively small when compared to the unit runoff in other parts of Arizona; however, the unit runoff is extremely high for the eastern Grand Canyon area. An inspection of the general area indicated that some streams had the largest flows of any that have taken

TABLE 2.—*Channel conditions and estimated discharge at selected sites in eastern Grand Canyon, Flood of December 1966*

[Channel properties were studied in detail at the six slope-area measurement sites; elsewhere, channel width, depth, and discharge values were estimated by visual inspection or approximate measurement. For broad U-shaped channels, top widths were measured at the cross sections that were used to estimate discharge; for narrow U-shaped channels, an average width is given. Channel depth generally is the maximum depth above channel bottom. For channels having shallow overflow areas, the properties listed are for the main channel; at some sites, channel properties were determined using the average of measurements at several sections. Velocities used to compute discharge were estimated from the measured velocities of similar streams outside the Grand Canyon area; the values are approximate but are sufficiently accurate to indicate the order of magnitude of flow. Height of terrace or terracelike feature above streambed: B, channel cut in bedrock; D, ditch; H, depth of channel below headcut; J, discontinuous channel; M, channel modified by manmade structure; <, less than; >, more than; /, separates different terrace levels]

Site number (located on pl. 1)	Stream	Drainage area (mi²)	Channel width (ft)	Channel depth (ft)	Estimated discharge: Cubic feet per second	Estimated discharge: Cubic feet per second per square mile	Height of terrace or terracelike feature above streambed (ft)	Channel description
	North Canyon Wash basin							
1	Upper North Canyon	4.11	15	0.3	4	1.0	1	Mainly grass-covered flood plain.
2	North Canyon Wash	24.6	10	4	800	[1]32	5	Channel irregular and controlled by sagebrush and other brushy vegetation. Channel was widened and deepened about a foot during the 1966 flood. Upstream from site 2, gravel bars restrict the channel and cause from 2 to 3 ft of local lateral cutting and overflow on the adjacent flood plain.
3	Upper Tater Canyon	5.82	25	1.5	85	15	3	Discontinuous gully less than 3 ft deep; the 1966 flood caused minor erosion; some gullies in Del Motte Park were extended 1–3 ft headward.
4	do	15.0	20	<.2	10	.7	<1	Grass-covered flood plain.
5	Tater Canyon	34.3	8	1	5	.3	2	Channel irregular and controlled by sagebrush and other brushy vegetation; slightly affected by the 1966 flood.
6	Pleasant Valley outlet	7.24	--	--	[2]	--	<1	Grass-covered flood plain; few limestone sinkholes.
	South Canyon Wash basin							
7	South Canyon	6.65	25	1.5	200	30	<3/5–6/15–16(?)	Channel shows slight effects of the 1966 flood.
8	South Canyon tributary 1	5.83	9	3	250	42	2/4–5/7/14(?)	Channel slightly to moderately affected by the 1966 flood; most of the streamflow in South Canyon Wash basin was along this tributary. Part of the alluvium that forms the 4–5-ft-high terrace contains abundant charcoal and carbonaceous material. The alluvium was derived from an area denuded by a forest fire in the headwaters of the drainage; the fire occurred in 1960 and burned about 9,000 acres (C. M. Fauley, Park Forester, oral commun., 1968).
9	South Canyon tributary 2	3.47	10	1	75	22	1–3/5–6	Channel not affected appreciably by 1966 flood.
10	Fence Canyon	5.24	15	2.5	200	38	3–3½/8	The flood in the summer of 1967 deepened the channel more than the flood of 1966; in places lateral cutting has removed less than 5 ft of gravel from the sides of the 8-ft terrace; gravel bars in the straighter and wider parts of the channel caused overflow on the 3–3½-ft-high terrace.
11	Fence Canyon tributary	6.25	28	2.2	250	40	4	Gravel bars were deposited in the channel by the 1966 flood; some vertical banks were cut.
12	Wildcat Canyon	10.9	20	3	350	29	2–3/6/8	Channel moderately affected by the 1966 flood.
13	Wildcat Canyon tributary	1.3	--	--	[2]	--	2–3/5	Channel swept relatively clean by a pre-1966 flood; root crown of a 3-ft-diameter juniper along the streambed indicates that the channel depth has been stable for the last few centuries.
	Buck Farm Canyon basin							
14	Buck Farm Canyon Wash	2.57	7	2	100	39	2–3	Channel irregular and controlled largely by sagebrush and juniper. The channel was little affected by the 1966 flood, although some scouring occurred; flow filled a 6-ft-wide channel of a tributary to Buck Farm Canyon Wash to a depth of only a foot.
	Nankoweap Creek basin							
15	Nankoweap Creek	16.4	80	5	3,000	183	5–6(?)/8/14	Channel modified by the 1966 flood.
16	Nankoweap Creek tributary	7.16	50	3.5	800	112	3–4	Channel partly modified by the 1966 flood. Channel was straightened and smoothed and loose rocks and brush were removed; in places the flow moved through flood channels or chutes, thereby shortcutting meanders; minor lateral cutting.
	Kwagunt Creek basin							
17	Kwagunt Creek	4.67	50	4.5	1,200	260	4/7–8/11/17–18	Channel modified by the 1966 flood.
	Chuar Creek basin							
18	Chuar Creek	3.13	<10	0.1	<0.5	0.1	3±	Channel was not modified by the 1966 flood.
19	Lava Creek	3.18	40	4	--	--	2–3/5/8/12/30	The flood of 1966 caused considerable scouring and deposition of gravel bars; brush protected the sides of the channel from extensive erosion; century plants growing on the 3-ft and higher terraces indicate that the terraces are not flooded often.
20	Natchi Canyon	3.45	50	16	--	--	12/15/23	Mudflow caused by the 1966 flood severely modified channel.
21	Lava Creek	9.03	15	6	800	[3]89	5–6/15–18/25	Mudflow caused by the 1966 flood slightly modified channel.

See footnotes at end of table.

TABLE 2.—*Channel conditions and estimated discharge at selected sites in eastern Grand Canyon, flood of December 1966*—Continued

Site number (located on pl. 1)	Stream	Drainage area (mi^2)	Channel width (ft)	Channel depth (ft)	Estimated discharge: Cubic feet per second	Estimated discharge: Cubic feet per second per square mile	Height of terrace or terracelike feature above streambed (ft)	Channel description
	Clear Creek basin							
22	Clear Creek tributary 1	0.79	15	0.15	<1	1	None	Grass-covered flood plain.
23	Clear Creek tributary 2	.86	25	1	35	41	<1	Grass-covered flood plain; the 1966 flood cut a few irregular scours that are 1 ft deep and as much as 4 ft wide and 20 ft long.
24	Clear Creek tributary 3	3.63	60	2	350	97	2	The 1966 flood deepened old scours, formed new scours, and deposited gravel bars; most scours are less than 2 ft deep, 6 ft wide, and 20 ft long; two large scours are 100 and 300 ft long; one large gravel bar is about 100 ft long and has a maximum thickness of 1½ ft.
25	Walhalla Glades	1.32	4	2	20	15	<2	The 1966 flood cut a few scours less than ½ ft deep and 3 ft long; ponderosa pine root crowns ½–2 ft in diameter occur along the streambed.
26	do	4.54	14	1.7	[4]66	15	1/1½–2	The 1966 flood cut shallow scours and deposited a few thin poorly formed gravel bars; the scours generally are from 1 to 1¼ ft deep, 4 ft wide, and about 6 ft long; however, one scour is 50 ft long.
	Bright Angel Creek basin							
27	Bright Angel Creek	5.28	2	0.2	0.2	<0.1	<1	Flood plain and channel contain shallow discontinuous depressions covered by grass; the 1966 flood caused minor erosion but did not cut any new scours.
28	Bright Angel Creek tributary	<.08	4	1	8	>100	<1	Grass-covered flood plain.
29	Thompson Canyon	13.45	--	--	([2])	--	<1	Grass-covered flood plain; no appreciable erosion during the 1966 flood or other recent floods.
30	Fuller Canyon	2.4	15	<.5	10	4	3MH	The 1966 flood renewed scouring in an old healed gully.
31	do	3.49	15	3.5	[4]167	[5]48	5D	The 1966 flood caused minor erosion in a grass-covered ditch.
32	Thompson Canyon	23.3	6	4.5	150	6	3–4/7H	The 1966 flood caused some scouring and lateral cutting. A pile of flood debris consists mainly of logs; the logs are at angles of as much as 45° in the lower part of the pile and indicate a conduit or sinkhole in the streambed near Bright Angel Spring; the debris pile intercepted part of the streamflow, which may have recharged Roaring Springs.
33	The Transept tributary	.96	80	.5	7	7	<1	Grass-covered flood plain; the effects of the 1966 flood are negligible.
34	Outlet Canyon	2.02	--	--	([2])	--	1–4MJ	During the 1966 flood, grass-covered channels were filled to depths of about a foot, which caused minor scouring and deposition of a few thin bars and some lag gravel; a prominent scour near the head of the canyon about 2 mi upstream from site 34 and at least one scour in Upper Little Park were present before the 1966 flood and indicate that this area was less affected by the 1966 flood than by other recent floods.
35	do	9.42	40	4	[4]414	[6]44	2–3/5½–11	The 1966 flood moderately affected the channel, which is fairly straight; the flood cut new scours 1 ft deep and 30 to 50 feet long in the bottom of the grass-covered channel.
36	Outlet Canyon tributary 2	.5	25	2.5	80	160	3	The 1966 flood was confined mainly to gullies eroded before 1966. The flood deepened old gullies, cut new scours, eroded the roadbed of Point Sublime Trail, and deposited some gravel. New scours are present in about 20 percent of the channel; some of the new scours are as much as 5 ft deep. In the broad meadow upstream from where the Point Sublime Trail crosses the channel effects of the 1966 flood are negligible.
37	Bright Angel Creek	101	60	6	[4]4,000	40	6–8	The 1966 flood caused major channel modification and lateral cutting.
	Crystal Creek basin							
38	Crystal Creek	2.41	6	2	12	5	1–3	Grass-covered channel and flood plain; the 1966 flood caused minor scouring, and much of the channel and canyon floor was essentially undisturbed.
39	do	12.1	10	3	100	9	2/10–12	The 1966 flood caused some scouring and deposition of gravel bars in the channel and flood plain, which are covered by vegetation; in places 6-ft-high terraces were inundated; scours generally are 5–10 ft long and 1–2 ft deep; maximum lateral cutting was 3 ft.
40	Dragon Creek	4.58	15	8	1,000	220	7/12/15/25–26	The 1966 flood modified the channel, eroded low flood terraces, and removed vegetation.
41	Milk Creek	1.38	45	2	120	87	<2J	The 1966 flood cut a few scours as much as 1½ ft deep, 4 ft wide, and 10 ft long in the grass-covered discontinuous channel; a considerable part of the flow was from an east-flowing tributary.
42	Milk Creek tributary	.44	20	2	30	68	1–2/3–4	The 1966 flood caused minor scouring in the partly grass-covered channel.
43	Milk Creek	6.82	60	25	--	--	12/35±	Mudflow caused by the 1966 flood severely damaged the channel.
44	Dragon Creek tributary 1	4.19	15	3	40	10	5–6	Channel slightly modified by the 1966 flood.
45	Dragon Creek tributary 2	1.57	10	<.5	10	6	<5	Channel was not modified by the 1966 flood; however, a 12-ft dropoff was cut at the mouth by Dragon Creek.
46	Dragon Creek	19.2	60	20	[4]29,200	([7])	14–16/25	Mudflow caused by the 1966 flood severely damaged the channel.

See footnotes at end of table.

TABLE 2.—*Channel conditions and estimated discharge at selected sites in eastern Grand Canyon, flood of December 1966*—Continued

Site number (located on pl. 1)	Stream	Drainage area (mi²)	Channel width (ft)	Channel depth (ft)	Estimated discharge: Cubic feet per second	Estimated discharge: Cubic feet per second per square mile	Height of terrace or terracelike feature above streambed (ft)	Channel description
					Tuna Creek basin			
47	Walla Valley Wash	8.27	3	0.25	<1	0.1	<1	Grass-covered flood plain has a local relief of less than 1 ft.
48	Walla Valley tributary	.77	3	.1	<.5	.6	<2	Channel and flood plain covered by grass and litter.
					Shinumo Creek basin			
49	Big Spring Canyon	5.97	25	1.5	25	5	<1	The 1966 flood cut a few scours in the grass-covered flood plain, which has discontinuous channels less than 2 ft deep.
50	Tipover Canyon	5.42	3	1	4	.8	2	The 1966 flood caused minor scouring and deposition of small gravel bars in the discontinuous pre-1966 arroyo; in places the arroyo is as much as 6 ft deep.
51	Kanab Canyon	5.16	25	1	15	3	<1	Grass-covered flood plain; effects of the 1966 flood are negligible.
52	Kanabownits Canyon	9.75	20	1	<100	10	2	The 1966 flood washed out the road in places and scoured the channel. The pre-1966 channel was 1 to 2 ft deep and generally was less than 5 ft wide; the 1966 floodflow cut scours 3 ft deep, 5 ft wide, and as much as 30 ft long.
53	Kanabownits Canyon tributary	1.38	--	--	([2])	--	<1	Grass-covered flood plain; little evidence of recent streamflow is apparent.
54	Shinumo Creek	67.4	50	6	[4]1,660	[8]24.7	4–6/10	The 1966 flood caused only minor scouring because the dense riparian vegetation protected the channel from erosion.
55	White Creek	14.4	20	2.5	120	8	4–5/8	The 1966 flood was not as large as a previous flood.
					Tapeats Creek basin			
56	Quaking Aspen Canyon	9.38	--	--	([2])	--	3½H	A pre-1966 arroyo does not show evidence of recent flow.
--	Crazy Jug Canyon tributaries	([9])	--	--	--	--	<5–<5B	
57	Browns Canyon	2.23	2.5	1.5	5	2	<1	Grass and reed-covered flood plain; dense vegetation protected the channel from erosion during the 1966 flood.
58	Tapeats Creek	82.7	30	2	400	5	5/8–10/30±	The 1966 flood was not as large as previous floods.
					Deer Creek basin			
59	Deer Creek	16.7	25	3.5	300	18	2–4/7/10/19–20	Channel only slightly modified by 1966 flood owing to the dense riparian vegetation; the flood eroded and enlarged scours from 1 to 3 ft deep and less than 12 ft long.
					Kanab Creek basin			
60	Lookout Canyon	10.3	--	--	([2])	--	<1	Grass-covered flood plain.
61	Dry Park Wash	5.96	--	--	([2])	--	<1	Do.

[1]Upper part of basin did not contribute runoff to the flood. Unit runoff from the contributing area probably was at least 60 ft³/s per mi².
[2]No high watermarks or other flood evidence were found. If flow did occur, the amount was very small.
[3]All water was from Natchi Canyon and Lava Creek above Natchi Canyon—a combined drainage area 6.63 mi². Unit runoff from this area probably was more than 120 ft³/s per mi².
[4]Discharge measured by slope-area method.
[5]Most of the flow was from about 0.6 mi² of the drainage area. Unit runoff was about 300 ft³/s per mi².
[6]Upper part of the basin contributed very little runoff to the flood. Unit runoff from the contributing area probably was more than 70 ft³/s per mi².
[7]Unit runoff was not applicable because a large percentage of the flow was rock and mud.
[8]Flow was from the lower half of the basin. Unit runoff from the contributing area ranged from 50 to 100 ft³/s per mi².
[9]Aerial inspection showed no evidence of high flows in Parissawampits, Locust, or Timp Canyons or in other tributaries to Crazy Jug Canyon. The area was not inspected on the ground.

place in the last few hundred years. Gaging-station records for Bright Angel Creek show that the magnitude of the peak discharge was not as unusual as the volume of flow during the flood period.

Many mudflows and debris slides accompanied the large flows in the uninhabited gorges in Nankoweap, Kwagunt, Lava, Clear, Crystal, and Shinumo basins (pl. 1; table 2). The flood at site 15 in Nankoweap Creek (pl. 1; fig. 3) had an estimated peak discharge of 3,000 ft³/s (85 m³/s) and may have been the largest flood along this drainage in historical times. Mudflows and debris slides that originated in the upper drainage area of Lava Creek caused severe changes in channel geometry. Site 21 in Lava Creek had an estimated peak discharge of 800 ft³/s (20 m³/s), most of which came from the 6 mi² (16 km²) above the confluence of Lava Creek and Natchi Canyon. Although a large unit runoff occurred from the high headwaters of Kwagunt Creek, the 1966 flood was not an exceptional event in this drainage. Considerable erosion took place along Clear Creek, where the discharge probably greatly exceeded that from Walhalla Plateau (table 2).

Little runoff from the headwaters of Big Spring, Kanab, and Kanabownits Canyons reached Shinumo

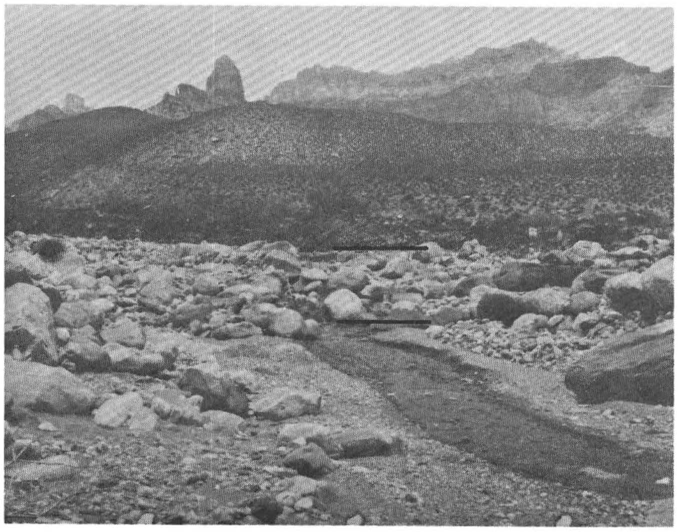


FIGURE 3.—Gravel bar at site 15 in Nankoweap Creek. View looking upstream. Height of bar (indicated by lines at base and top of bar) averages 5–6 ft (1.5–1.8 m).

Creek. Flood evidence indicates that less than 10 percent of the 1,660 ft^3/s (47.0 m^3/s) measured at site 54 in Shinumo Creek (fig. 4) came from the Kaibab Plateau. The flows above site 54 were mainly from precipitation on the canyon walls surrounding Modred and Merlin Abysses. At the old campsite of Bass near the mouth of Shinumo Creek (pl. 1), floodmarks indicate a maximum flow depth of only a few feet, but floatable camp debris less than 1 ft (0.3 m) above the floodmarks indicates that the flood may have been the highest since the camp was abandoned in about 1900. Regional flood-frequency studies indicate that a flood of this magnitude has a recurrence interval—the average number of years, during a long period of time, in which a given discharge will be equaled or exceeded—of almost 20 years. The recurrence interval is a measure of the magnitude of a flood and does not indicate the amount of time between such floods. The recurrence interval may be obtained from an analysis of data collected at a particular site or from a regional flood-frequency analysis. In this study the log-Pearson Type III distribution (Benson, 1968) was used for the analysis of station data.

Considerable runoff occurred in the area along the Cocks Comb in the drainage basins of North and South Canyons (table 2); however, the height of the floodmarks relative to the height of the low terraces in these canyons indicates that the peak discharge was not unusual. For example, in the Fence Canyon drainage basin the debris marks of a flood that occurred in the summer of 1967 are at about the same level as those of December 1966.

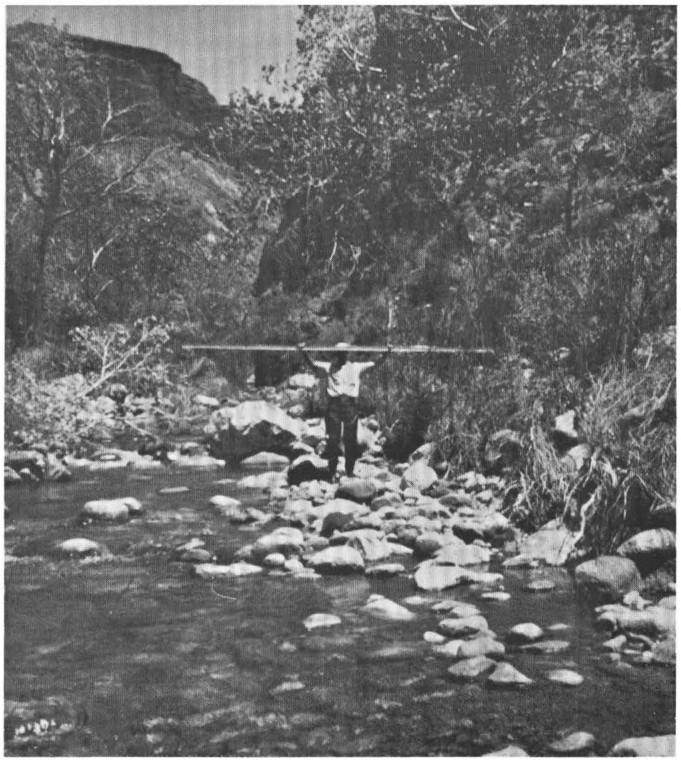


FIGURE 4.—Shinumo Creek at site 54. View looking upstream. The crest of the flood (indicated by level rod) was about 5½ ft (1.7 m) above the creekbed and did not inundate the terraces 6 ft (1.8 m) above the bed. At this site, the floodflow cleared only the bed because the sides of the channel and the terraces were protected by dense riparian vegetation.

BRIGHT ANGEL CREEK BASIN

Bright Angel Creek and the Colorado River are the only gaged streams in the flood area. Prior to the flood, recorders were in operation along Bright Angel Creek near the mouth and at Phantom Ranch. The station at Phantom Ranch was destroyed during the flood. The station near the mouth recorded only a part of the rise of the flood. The partial flood hydrograph indicates that the creek began to rise the morning of December 5 and continued in several steps to the peak on December 6. The recorder trace appears to have been rising when the recorder stopped operating about 0700 hours on December 6; the discharge was between 1,500 and 1,800 ft^3/s (42 and 51 m^3/s). A peak discharge of 4,000 ft^3/s (110 m^3/s) was determined for Bright Angel Creek by the slope-area method. The peak discharge of Bright Angel Creek during the flood of December 1966 was the second largest in 45 years, having been exceeded by the flood of August 1936. The recurrence interval computed from a log-Pearson Type III distribution (Benson, 1968) is about 50 years, and that obtained from the regional flood-frequency relation developed by Patterson and

Somers (1966) is about 100 years. The flood-frequency relation derived from the log-Pearson Type III distribution and station data and that derived from the regional analysis of Patterson and Somers (1966) may be compared using curves A and B in figure 5. The plotting position of the data points was obtained from the equation

$$RI = \frac{N+1}{M},$$

where

RI = recurrence interval, in years,
N = number of years of record, and
M = order number.

The order number, M, was assigned as follows. The annual maximum discharge for each water year was arrayed in order of magnitude and assigned an order number—the largest being number 1, the second largest number 2, and so forth.

The peak discharge of 4,000 ft^3/s (110 m^3/s) on December 6, 1966, at the Bright Angel Creek gaging station was less than that of 4,400 ft^3/s (120 m^3/s) on August 19, 1936. The 1966 flood was much more damaging, however, because high flows persisted for a longer time and because the volume of water that flowed past the station during the 1966 flood was several times larger than that during the 1936 flood. The mean flow for August 19, 1936, was only 200 ft^3/s (6 m^3/s), whereas, the mean flow for December 6, 1966, was estimated to be 2,500 ft^3/s or 71 m^3/s (U.S. Geological Survey, 1968). The estimate for 1966 was based on information furnished by residents and discharge records for Kanab Creek and the Paria River. A plot of maximum daily means for the 44-year period indicates a recurrence interval of more than 100 years for a daily flow of 2,500 ft^3/s (71 m^3/s). (See fig. 5.) The highest mean flow for 3 consecutive days during the flood of December 1966 was 1,270 ft^3/s (36.0 m^3/s). The previous recorded maximum 3-day mean was 749 ft^3/s (21.2 m^3/s) in December 1941.

Slope-area measurements along Bright Angel Creek near Phantom Ranch at site 37 and in the tributary basins of Outlet Canyon at site 35 and Fuller Canyon at site 31 on the Kaibab Plateau indicate that the average unit runoff for the 1966 flood was between 40 and 48 ft^3/s per mi^2 (0.44 and 0.52 m^3/s per km^2). (See pl. 1; table 2.) Locally, the unit runoff exceeded this amount several times. For example, the flow in Fuller Canyon was mainly from a 0.6 mi^2 (1.6 km^2) area and the runoff rate was nearly 300 ft^3/s per mi^2 (3.3 m^3/s per km^2).

The precipitation from the storm of December 1966 had a marked effect on the flow of the springs near the head of Bright Angel Canyon. On December 9, 1966, the combined flow of Roaring Springs in Roaring Springs Canyon—a tributary of Bright Angel Canyon—was estimated to be 150 ft^3/s or 4.2 m^3/s (J. B. Gillespie and E. H. McGavock, written commun., 1967); the maximum flow was estimated to have been nearly 200 ft^3/s (5.7m^3/s). The normal discharge of the springs ranges from 5 to 15 ft^3/s or 0.14 to 0.42 m^3/s (Johnson and Sanderson, 1968, fig. 3). Gillespie and McGavock (written commun., 1967) estimated that an additional 75

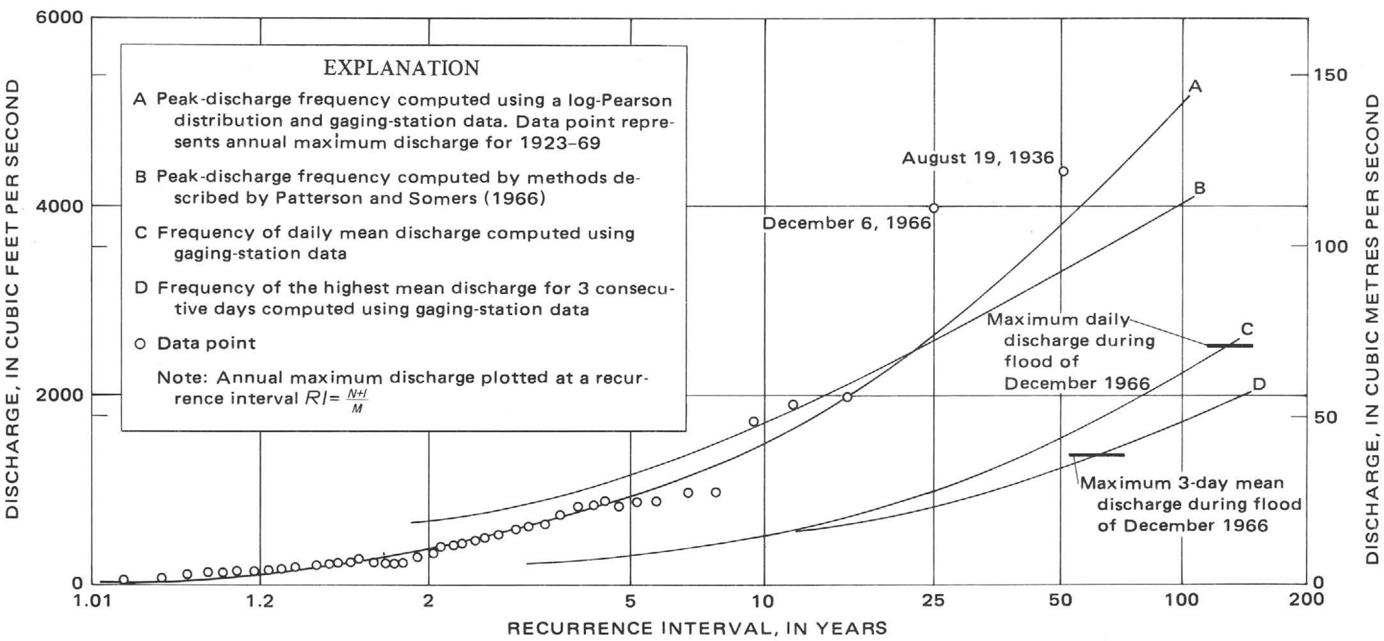


FIGURE 5.—Frequency of annual peak discharges, maximum daily mean flows, and highest mean flows for 3 consecutive days, Bright Angel Creek near Grand Canyon, Ariz.

ft^3/s (2.1 m^3/s) came from two unnamed springs a short distance downstream from Roaring Springs. Waldo Wilcox (National Park Service, oral commun., 1967) reported that the water emerging from Roaring Springs was red and muddy on December 7, and Gillespie and McGavock reported that the water was not muddy but had a yellowish discoloration on December 9.

CRYSTAL CREEK BASIN

Along Dragon Creek, an undeveloped tributary to Crystal Creek, the peak streamflow during the flood could not be measured by the slope-area method because a mudflow obscured the floodmarks. The mudflow—an aggregate of onrushing water, mud, rocks, and logs derived from soil, colluvium, debris slides, or avalanches—accompanied the high flow. The discharge, however, appears to have been greater in Dragon Creek than in Bright Angel Creek. Near site 46, a mescal pit—an underground pit for roasting *Agave* (century plant)—used by the Pueblo Indians about A.D. 1100 was destroyed or covered by mud; the mudflow lapped along the edge of a stone ring that borders another mescal cooking pit in use during the same period in the Hindu Amphitheater (see sections "Relation of Prehistoric and Historic Occupation to Flooding" and "Effects of Floods in the Tributary Gorges of Grand Canyon—Flood of December 1966 and Previous Recent Floods"). The information collected at these sites indicates that the stage of the mudflow of December 1966 was the highest in the last 800 to 900 years.

At site 46, a transit survey of the highest level reached by the mudflow showed a surface slope of 15.1 ft (4.60 m) in 256 ft (78.0 m), or 5.9 percent. The cross-sectional area was measured at three places along the channel and ranged from 1,180 to 1,330 ft^2 (110 to 124 m^2). A flow of 29,000 ft^3/s (820 m^3/s) was computed using the Manning equation and a roughness coefficient of 0.070. The Manning equation is

$$V = 1.486 \; \frac{1.486}{n} \; R^{2/3} \; S_e^{1/2}$$

in which

V = mean cross-sectional velocity of flow, in feet per second;

R = hydraulic radius at a cross section, which is the cross-sectional area divided by the wetted perimeter, in feet;

S_e = energy slope; and

n = coefficient of roughness.

At the time of the survey, mud and sand were plastered more than 1 in. (25 mm) thick on boulders, trees, and high on the sides of the channel. Locally, mud deposited on adjacent terraces appears to have flowed outward from the main body of flow. The edges of the mud stood in lobes about ½–1 in. (13–25 mm) above the ground, which indicates that the surface of the mudflow probably had the consistency of cake dough. The mud flowed over ridges and obstructions instead of around them. An air-dried sample of the mud was taken at the mouth of Crystal Creek; in the laboratory the dried mud sample was mixed with enough water to allow it to flow and produce a lobe similar to that at the edge of the mudflow shown in figure 6; the mixed laboratory sample contained about 40 percent water by volume. The mudflow was 18–20 ft (5.5–6.1 m) deep in the 60-ft-wide (18-m-wide) channel (fig. 7). In most places the depth of sustained flow of the water that followed the mudflow was about two-thirds that of the mudflow. The mudflow was preceded by a high flow of water, but the magnitude of the streamflow cannot be determined.

The flow at site 40 in Dragon Creek above Milk Creek was fairly large—about 8 ft (2.4 m) deep in a box-shaped channel about 15 ft (4.6 m) wide. The discharge was estimated to be about 1,000 ft^3/s (28 m^3/s) from a drainage area of 4.58 mi^2 (11.9 km^2), which is one of the highest discharges per square mile in the flood area. In contrast, little flow passed site 39 in the main stem of Crystal Creek (fig. 8)—possibly 100 ft^3/s (2.8 m^3/s) from a drainage area of 12.1 mi^2 (31.3 km^2).

FLOOD DAMAGE TO MODERN STRUCTURES

The Bright Angel Creek basin is the only area in eastern Grand Canyon where modern structures exist

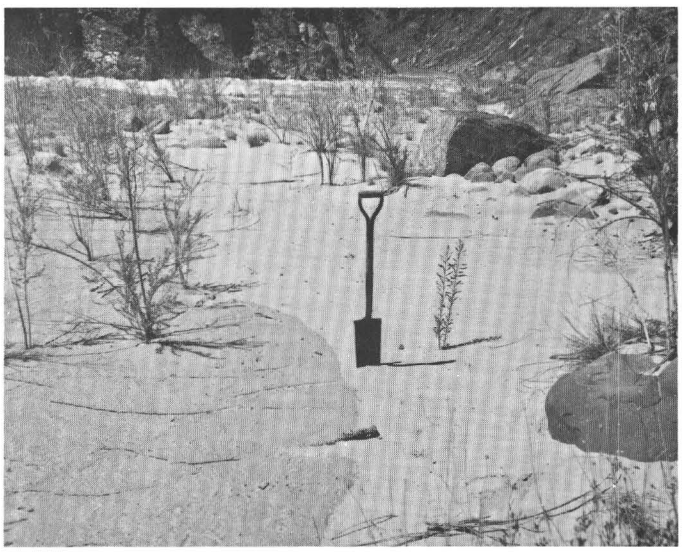


FIGURE 6.—Edge of the mudflow at the mouth of Crystal Creek where a sample was taken to estimate the consistency of the mud during the flood of December 1966. The mud (dark deposits) flowed over the preflood deposits (light deposits indicated by spade) of the Colorado River.

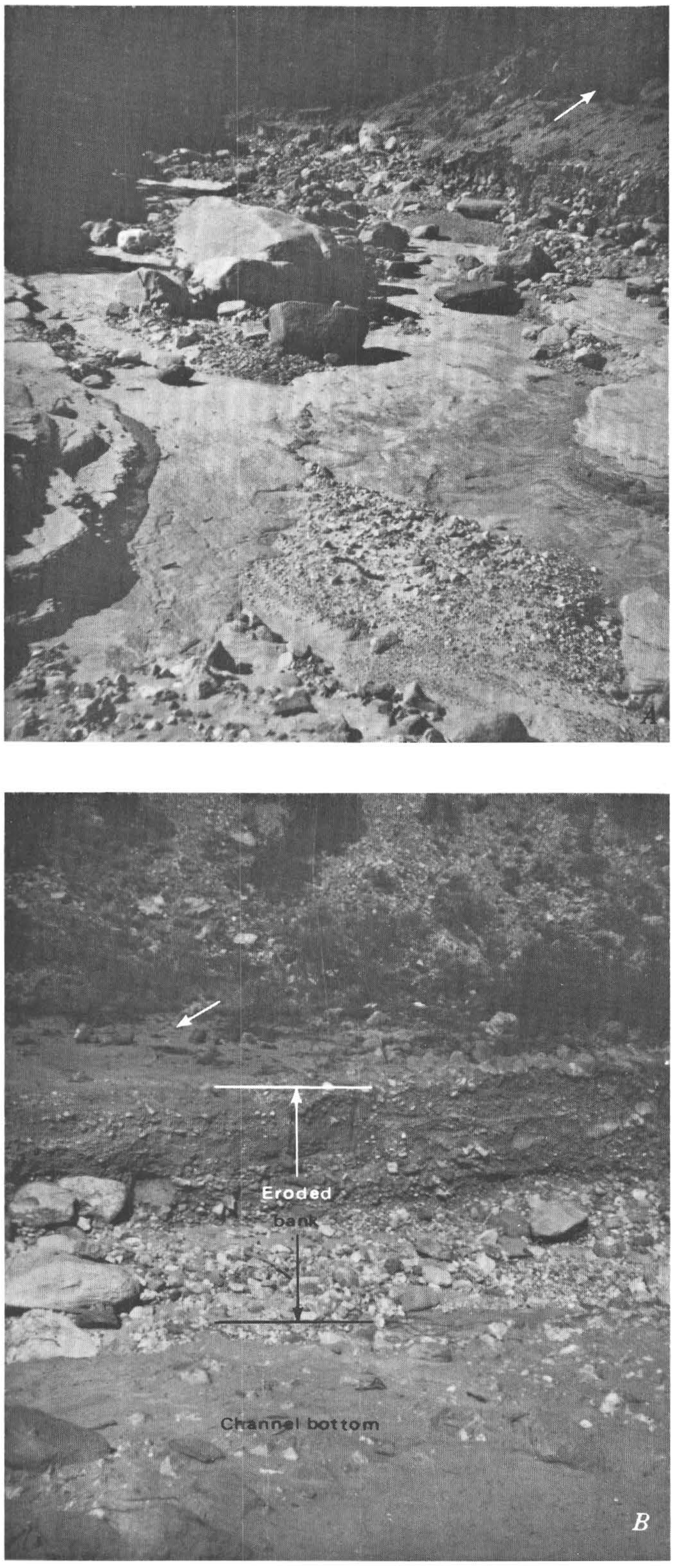


FIGURE 7.—Dragon Creek at site 46. Arrows indicate crest of mudflow. *A*, Looking downstream along the slope-area reach. Note channel scoured to clean bedrock. *B*, Looking across the channel from the east side. The height of the eroded west bank averages about 12 ft (3.7 m).

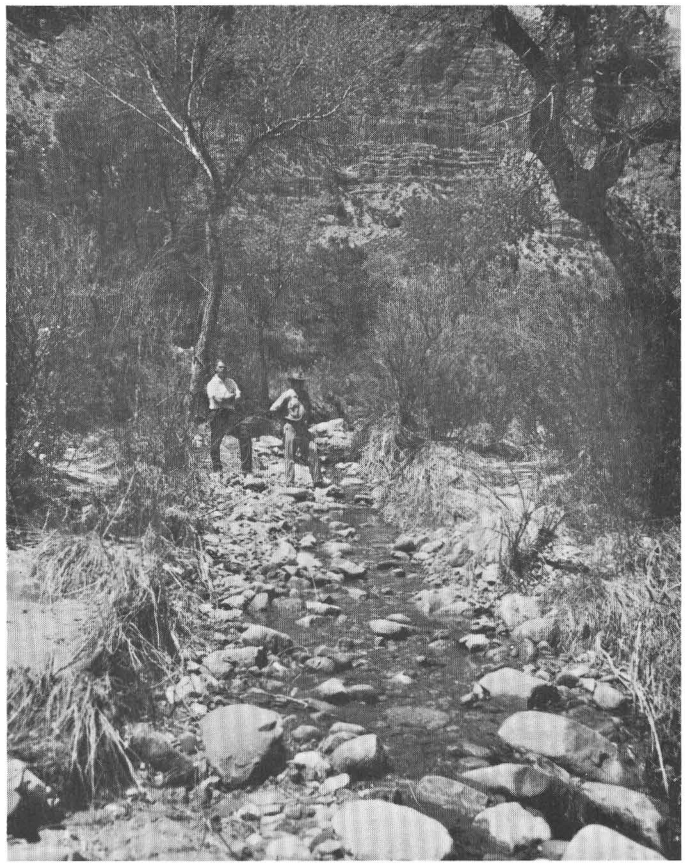


FIGURE 8.—Crystal Creek above Dragon Creek; looking upstream. The channel conditions in this reach probably are representative of those in most of Crystal Creek prior to the flood because the channel was changed little by the flood.

near a stream; these structures and roads on the Kaibab Plateau received considerable damage. Most of the road damage was near the Bright Angel Ranger Station, in Kanabownits Canyon, and along the road leading to Saddle Mountain in North and South Canyons. Because the cells of intense precipitation were centered in almost unpopulated parts of the Grand Canyon area, no loss of life occurred. Many more buildings and campgrounds would have been damaged with possible loss of life if Bright Angel Canyon had been subjected to the extensive mudflow activity that occurred in the undeveloped Crystal Creek area.

Flooding was not exceptionally severe in the North and South Canyon areas, but residents reported more washouts than during any other recent storm. Sections of the improved dirt road in the narrow part of Kanabownits Canyon were severly damaged and were almost impassable for automobile travel. Near the Bright Angel Ranger Station, debris slumped across the paved highway in Thompson Canyon and along the Point Sublime Trail east of Outlet Canyon (fig. 9). Several debris slides took place near Bright Angel Creek

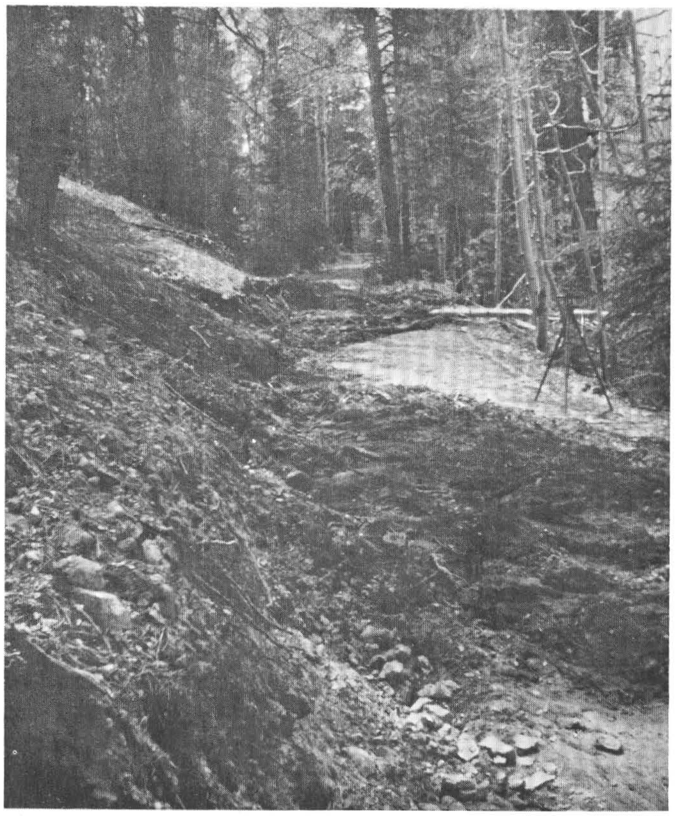


FIGURE 9.—Debris slide along the Point Sublime Trial 0.25 mi (0.4 km) east of Outlet Canyon.

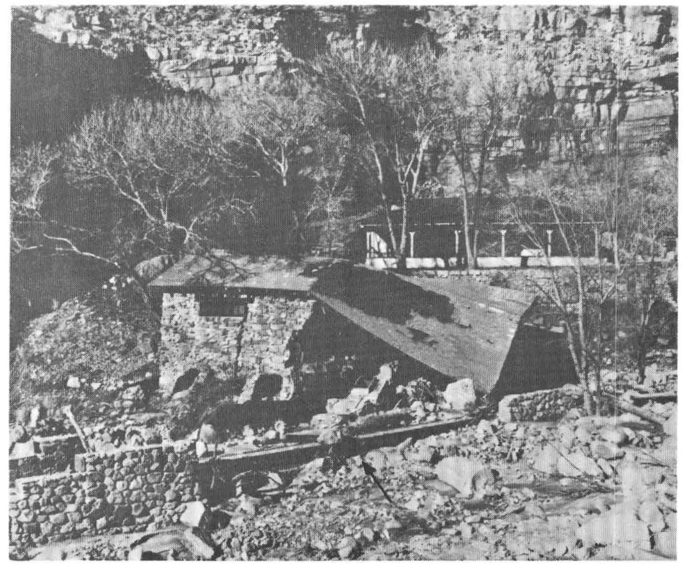


FIGURE 10.—Damage to structures in Bright Angel Canyon, flood of December 1966. Powerhouse in middle foreground, residence in right center, bridge and pipeline in foreground. The channel of Bright Angel Creek now is established behind the bridge and under the powerhouse. Note the debris on the bridge (arrow).

FIGURE 11.—Exposed pipeline (arrow 1) near Ribbon Falls. Prior to the flood, a 40-ft (12-m) bridge crossed Bright Angel Creek in the center of the photograph (arrow 2). The channel is now about 150 ft (46 m) wide and is bordered by a single terrace.

along the paved highway leading to Point Imperial and Cape Royal, and the highway was closed for several months.

The pumps at Roaring Springs in Bright Angel Canyon were damaged when about 2½ ft (0.8 m) of water from Roaring Springs Canyon rushed through the pumphouse. The powerhouse 0.50 mi (0.8 km) downstream on Bright Angel Creek was demolished (fig. 10). Between the pumphouse and the mouth of Bright Angel Creek, the flood washed out parts of the cross-canyon Kaibab Trail, bridges, and a $2 million pipeline that had just been completed to transport water from Roaring Springs to Phantom Ranch and Grand Canyon village (figs. 11, 12). The pipeline was in a shallow trench along the Kaibab Trail, which crosses Bright Angel Creek at several places between Phantom Ranch and Roaring Springs Canyon. Although a part of the pipeline was not washed out by the flood, it was plugged with gravel to such an extent that it was unusable. According to the National Park Service (written commun., July 1970) 3½ years and $5 million were required to rebuild the pipeline and repair the trail.

The flood caused severe damage to manmade structures near the Phantom Ranch and cut a new channel a few feet west of the recently constructed U.S. Geological Survey residency at the ranch; although floodwater surrounded the residency, the building was not damaged. The new channel cut through the nearby recreational grounds and undercut a corner of the wranglers' quarters (fig. 13). Near the mouth of Bright

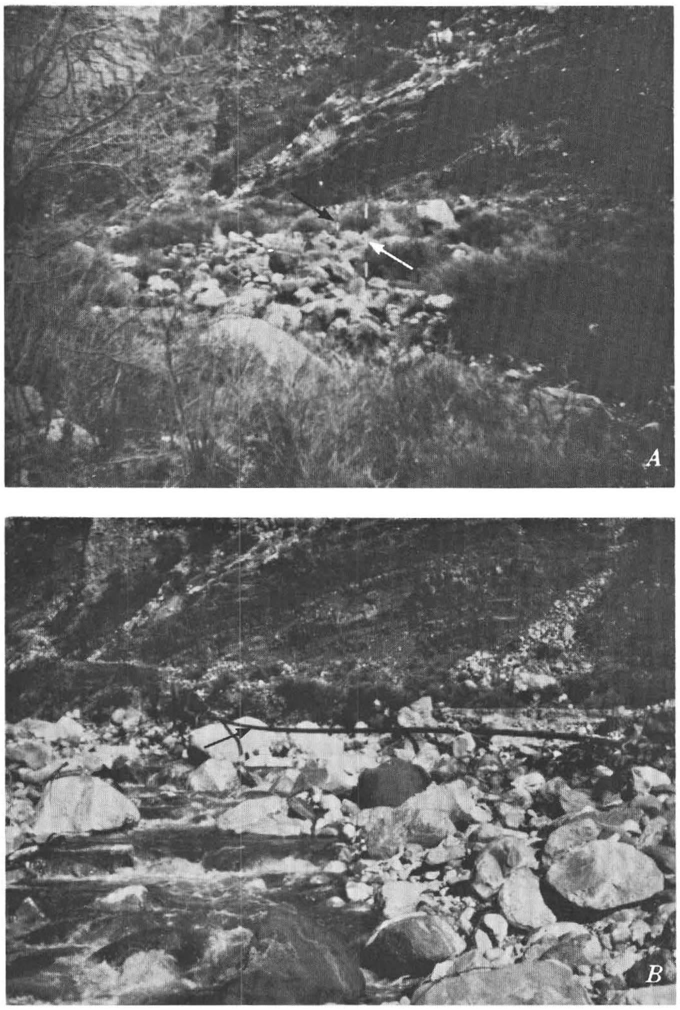


FIGURE 12.—Bright Angel Creek before and after the flood of December 1966. *A*, Stream channel before the flood; poles show the alinement of the pipeline (arrows). *B*, Exposed pipeline (arrow) after the flood.

Angel Creek, a large part of Phantom Ranch Campground was removed by lateral erosion (fig. 14).

RELATION OF PREHISTORIC AND HISTORIC OCCUPATION TO FLOODING

All the north rim tributary gorges damaged during the flood of December 1966 contained evidence of past human occupation, mainly in the form of ruins. The ruins were occupied by Anasazi Pueblo III Indians—direct ancestors of the Hopi Indians of northern Arizona—between A.D. 1050 and 1150. The prehistoric Indians must have experienced flash floods, but the flood of December 1966 probably was greater than any since the general abandonment of eastern Grand Canyon by the Pueblo Indians about A.D. 1150. At least

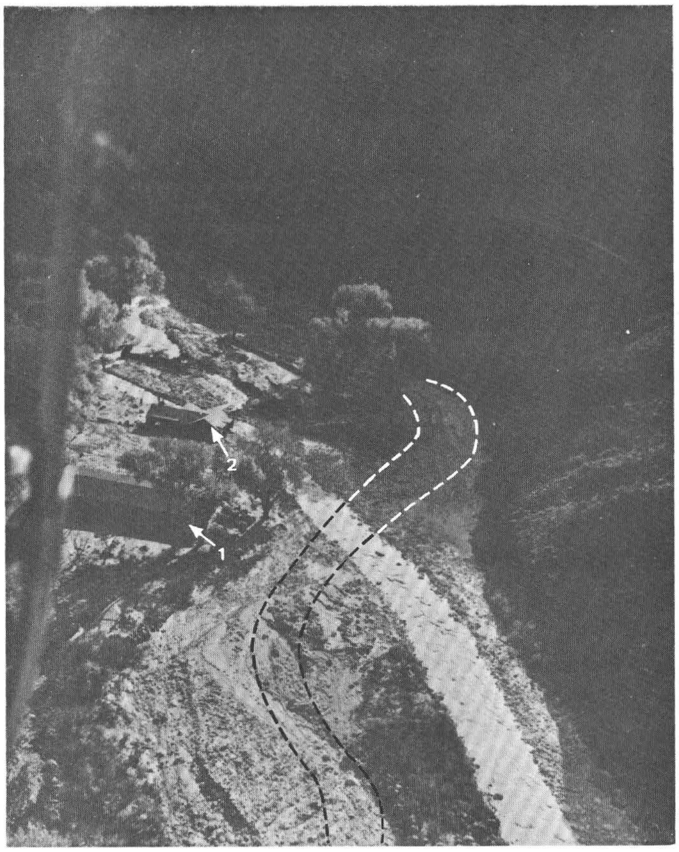


FIGURE 13.—Damage to structures near the Phantom Ranch, flood of December 1966. Aerial view looking downstream. U.S. Geological Survey residency is in left center (arrow 1). The new channel of Bright Angel Creek crosses the terrace between the Survey residency and the cottonwoods, and the creek flows under part of the wranglers' quarters (arrow 2). The undercut corner of the wranglers' quarters collapsed after this photograph was taken. Before the flood, the channel followed the approximate path indicated by the dashed lines.

three archeological sites,[2] unused and undisturbed since that time, either were obliterated or damaged during the 1966 flood.

Archeologists are able to diachronically describe the culture-history of the area in general terms from the surveys and analyses of more than 250 ruins recorded below the rims of the canyon (Euler, 1969, p. 8). Most of the archeological sites in the area affected by the 1966 flood were occupied by the Kayenta Anasazi Indians about A.D. 1050-1150. A few campsites, however, were used by the Southern Paiute Indians between about A.D. 1200 and the late 19th century and by the Hopi Indians after A.D. 1300; other sites are mine shafts

[2]In this paper, an archeological site may be considered to be any lasting evidence of human utilization, from a group of surface potsherds marking a former campsite to the clusters of ruined masonry structures, check dams, and mescal pits. Each site is recorded in the Prescott College Archaeological Survey and is given in this paper in parentheses—for example (Ariz. B:16:42).

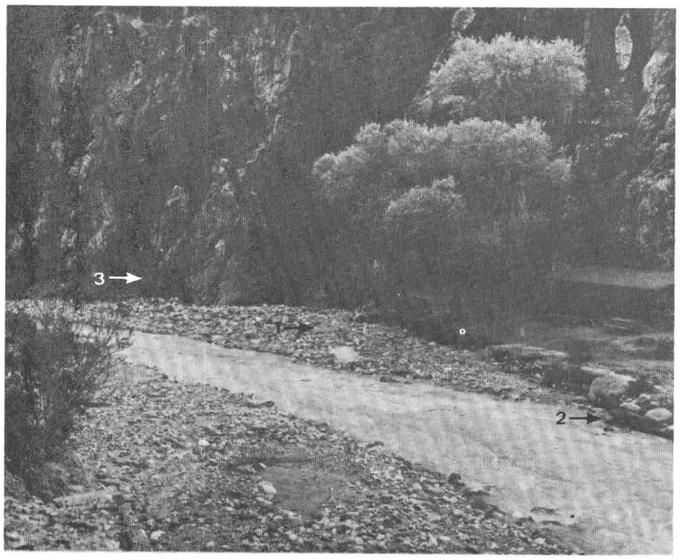


FIGURE 14.—Damage to the Phantom Ranch Campground, flood of December 1966. Prior to the flood, restrooms were located in the area in the center of photograph (arrow 1), and a bridge crossed the creek in the foreground (arrow 2) to provide access to the campground. The fireplace in left center (arrow 3) indicates the former ground level.

and cabins of the 19th century prospectors. The fact that more of the hundreds of Pueblo ruins have not been damaged or destroyed in Grand Canyon is due to their location on terraces and cliffs; therefore, it is suggested that the Anasazi were aware of the danger of periodic floods—although not as severe as the flood of 1966—and so built most of their structures in protected places. Mescal pits, such as those discussed in the following paragraphs, probably were of little consequence to the Anasazi and were built in unprotected places.

ARCHEOLOGICAL SITES IN THE FLOOD AREA

All the main gorges that drain from the north rim contain many early Pueblo III Kayenta Anasazi sites. The sites include surface rock shelters, masonry rooms, granaries, and mescal pits. Because most of these sites are away from the stream channels, only a few along Clear and Dragon Creeks (Crystal Creek basin) were damaged by the flood of December 1966. Only one historical site, the old campsite of Bass along Shinumo Creek, was endangered by the flood.

CLEAR CREEK

Evidence of a large flood was noted along Clear Creek, particularly in Ottoman Amphitheater where there are three archeological sites. The sites consist of surface masonry rooms, granaries, and one mescal pit. The mescal pit (Ariz. B:16:6) was first recorded in May 1966 as being 12 ft (3.7 m) in diameter and 35 ft (11 m) from the bed of Clear Creek. Lateral cutting by the flood of 1966, however, completely removed the western one-eighth of this cultural feature (fig. 15) and exposed a sherd (classified as Deadmans Fugitive Red, Cohonina culture) 1.6 ft (0.50 m) below the surface of the pit. Although the sherd was the only artifact recovered from the site, Euler believes that the mescal pit, like all other sites in Clear Creek Canyon, is a Kayenta Anasazi structure dating from about A.D. 1150.

CRYSTAL CREEK

The drainage area of Crystal Creek—which contains two major tributaries, Dragon and Milk Creeks—is one of the areas most severely affected by the flood of 1966. An early Pueblo III site (Ariz. B:16:42) is in Dragon Creek Canyon a few hundred yards above its junction with Crystal Creek. The ruins are on both sides of the creek and consist of a rock shelter, surface masonry rooms, and mescal pits. All date from A.D. 1100±50 years and were abandoned probably not later than A.D. 1150.

At site (Ariz. B:16:42), one of the mescal pits on the left bank is about 26 ft (8 m) in diameter. The exact distance from the mescal pit to the stream channel was not measured when the site was originally recorded on May 16, 1966; Euler's (written commun., 1966) field notes show the pit to have been "about fifteen feet back from the edge of an erosional precipice which dropped away about ten feet to the normal water level of the stream." After the flood, the edge of the terrace was only 3 ft (0.9 m) from the pit, and the mudflow line touched the stone ring that marks the circumference of the pit (fig. 16). The ring showed no effects of erosion. The stone ring enclosed a shallow depression. A short trench was excavated into the fill from the center of the depression outward through the external limits of the fire-cracked stone ring. It was found that the upper 1.6 ft (0.50 m) of material inside the pit was a sandy loam. The soil showed no interbedded layers of stream-laid sandy or silty material that may have been deposited by Dragon Creek if the pit had been inundated by a large flood since its construction in about A.D. 1100.

Prior to December 1966, an 8½–11-ft-diameter (2.6–3.4-m-diameter) mescal pit (Ariz. B:16:41) was recorded about 1.25 mi (2.0 km) upstream from site Ariz. B:16:42 on the right bank of Dragon Creek (fig. 17). Although no diagnostic cultural materials were found, it is assumed that the pit was used about A.D. 1050–1150, as were the other sites in the drainage. When the area was visited after the flood, all traces of the pit had been eradicated by the mudflow, which extended across the entire canyon floor (fig. 17).

SHINUMO CREEK

The perennial flow of Shinumo Creek is fed by White Creek, Flint Creek, and Modred Abyss. About 30 Kayenta Anasazi sites dating from about A.D. 1050–1150 are in the drainage. All the sites are on ledges or terraces above the flood plain and suffered no damage, even in the upper reaches of Modred Abyss where the water and mudflows were deep.

The historic winter camp (Ariz. B:15:49) of the late William W. Bass—a prospector and early tourist guide in the Grand Canyon—is near the mouth of Shinumo Creek. The camp was in use from about 1890 to 1910 and consisted of gardens, root cellar, tents, and some masonry retaining walls on both sides of the creek. A description of the camp and photographs taken during its use were documented by James (1911, p. 190-203), a noted author of the day. An iron stove at the camp is about 10 ft (3 m) above the bed of the creek, and the maximum height of the floodline, which is only 20 ft (6 m) from the stove, is about 7½ ft (2.3 m) above the bed. A rock retaining wall was built a short distance downstream from the camp—presumably to retard stream erosion—and the flood of 1966 wetted part of the wall; however, there is no indication of flood damage at the site. Although regional frequency analyses show the flood to have a recurrence interval of about 20 years, the flood probably was one of the largest that has occurred since the occupation of this site.

EFFECTS OF FLOODS ON THE KAIBAB PLATEAU—FLOOD OF DECEMBER 1966 AND PREVIOUS RECENT FLOODS

The Kaibab Plateau is characterized by broad grassy parks and valleys between forested slopes of pine and spruce. Dense grass not only covers the parks but is present on the sides and bottoms of the stream channels. The parks and valleys are mantled by dark gray generally clayey to silty alluvial or colluvial soil; many of the bordering limestone ridges are deeply weathered. In places the weathering is more than 50 ft (15 m)

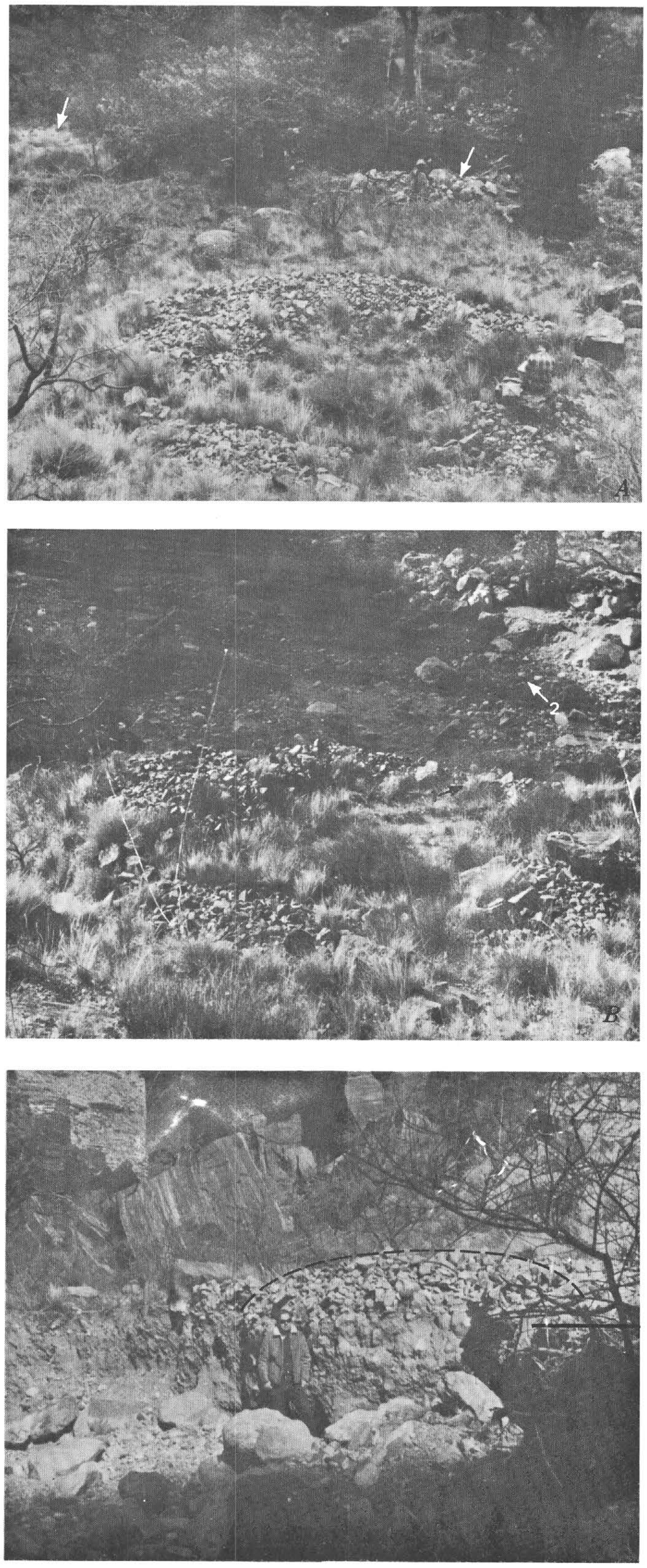


FIGURE 15.—Mescal pit (Ariz. B:16:6) damaged by the flood of December 1966 along Clear Creek. *A*, Undamaged mescal pit; man is on rim. Clogged channel of Clear Creek (arrows) in May 1966. *B*, Damaged mescal pit (arrow 1) and cleared channel of Clear Creek (arrow 2) in December 1968. Note that much of the dense vegetation has been removed and that a new pattern of large boulders has been established in the flood area. It appears that no significant new growth of vegetation occurred during the summer of 1968. *C*, Cross section of the mescal pit exposed mainly by lateral cutting during the flood. Rim of pit is indicated by dashed line. Depth of cutting is about equal to the height of the man. Wood debris (solid line) gives an indication of the flood crest.

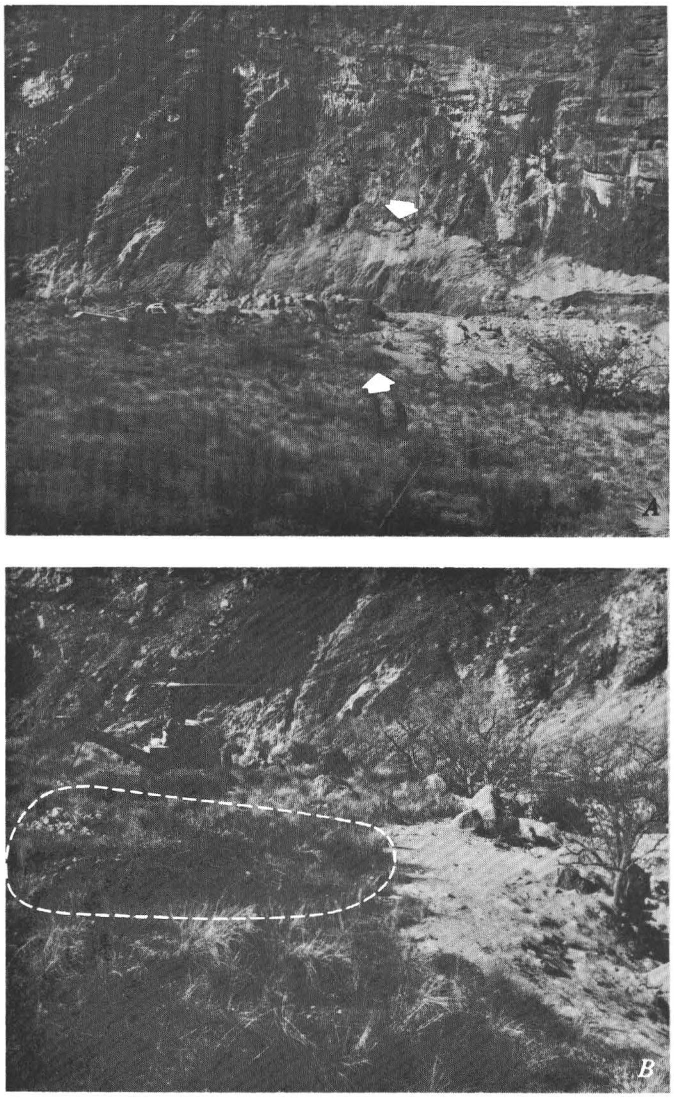


FIGURE 16.—Lower part of Dragon Creek at site (Ariz. B:16:42) after the flood of December 1966. *A*, Dragon Creek makes a sharp bend to the left at the base of the cliff; piling up of the mudflow accompanied by splash formed a 30-ft-high (9-m-high) crescent-shaped pattern (upper arrow) on the Vishnu Schist. Note edge of the mudflow (lower arrow) in foreground. Vegetation on the low terraces is mainly grass, *Agave*, Mormon tea, and catclaw, some of which indicate semiarid conditions. *B*, Closeup of mescal pit (dashed line) (Ariz. B:16:42) and edge of mudflow.

deep, and the limestone is covered by a loose residual accumulation of chert and limestone fragments. The fragments are used as roadbed material by the National Park Service and Arizona Highway Department.

In general, the surficial mantle and weathered limestone are permeable and tend to absorb precipitation and limit runoff, thereby restricting the formation of large channels. Many valleys display discontinuous channels or shallow channellike features that are generally less than 5 ft (1.5 m) deep and have a roughly trapezoidal cross section. In the southern part of Del Motte Park, in Little Park, along Clear Creek tributary 3, along the lower reaches of Fuller and Outlet Canyons, and in the Tipover Canyon and Quaking Aspen Canyon systems, a few gullies and arroyos were actively eroding before the flood of December 1966. Large parts of all the drainages on the Kaibab Plateau, particularly in the headwater reaches, are devoid of channels or channellike features.

FIGURE 17.—Mudflow debris on the terrace on the right bank of Dragon Creek (arrow). The location of mescal pit (Ariz. B:16:41), which was destroyed by the flood, is near that of the helicopter. Mudflow debris covers this area from canyon wall to canyon wall.

CLEAR CREEK BASIN

Clear Creek drains the Walhalla Plateau, which is part of the north rim area east of Bright Angel Canyon; of the tributaries to Clear Creek that were inspected, Walhalla Glades and Clear Creek tributary 3 showed the most effects from the flood of 1966. The channel of Walhalla Glades is continuous and is generally from 1½ to 2 ft (0.5 to 0.6 m) deep and from 5 to 12 ft (1.5 to 3.7 m) wide. The effects of the flood were much more apparent near Cape Royal (site 26) than in the area about 4 mi (6 km) north of the cape (site 25). At site 26 water overlapped the edge of the channel and covered part of the adjacent alluvial valley floor (fig. 18). From the borrow pit (pl. 1) to the edge of the Walhalla Plateau—a distance of about 0.50 mi (0.8 km)—the channel was scoured ½-2 ft (0.2-0.6 m). The new channel depth is between 2½ and 4 ft (0.8 and 1.2 m). Gravel from the borrow pit was transported downstream and acted as a cutting tool in deepening

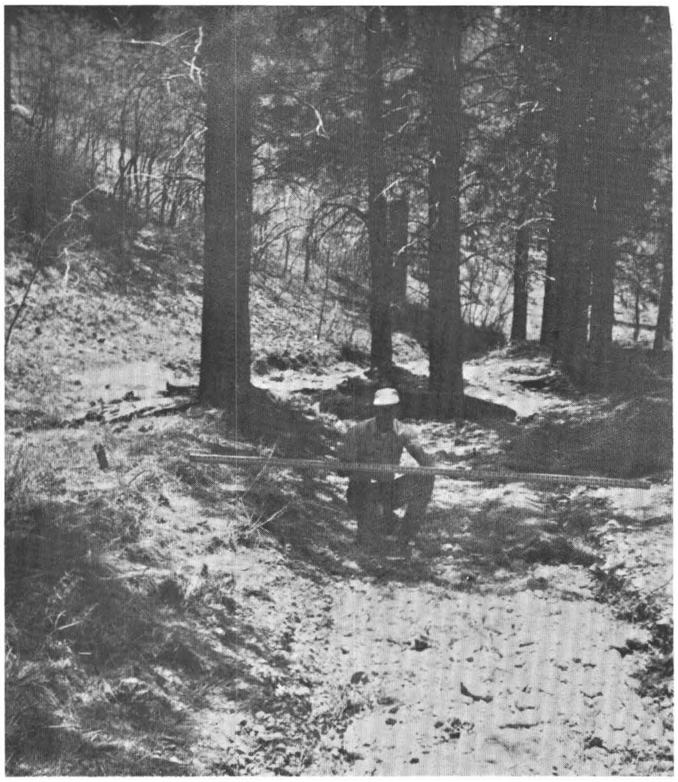


FIGURE 18.—Walhalla Glades at site 26. The flood of December 1966 deepened the channel—renewed arroyo cutting—by ½–2 ft (0.2–0.6 m) downstream from site 26; upstream the channel was deepened intermittently by scours. The low bench on the right side of the channel represents the level of the channel prior to the flood. Level rod indicates crest of the flood.

the channel; only discontinuous scouring occurred upstream from the pit (table 2).

Clear Creek tributary 3 is the main stream that drains the central part of the Walhalla Plateau. Prior to the flood of December 1966, the channel at site 24 was broad, in places having 2 ft (0.6 m) of relief. The channel displayed a few healed scours, but for the most part the pre-1966 channel was rather smooth. In most places the maximum depth of the flood was between 1½ and 2½ ft (0.5 and 0.8 m); the flood inundated the channel and a 50–75-ft-wide (15–23-m-wide) strip of the valley floor (fig. 19). The most conspicuous channel modification was the formation of scours and bars at irregular intervals (fig. 19*A*). The largest scour is about 300 ft (90 m) long (fig. 19*B*). The scour probably was being eroded before the flood because remnants of the grass-floored channel are present within the scour. The downstream part of the scour is partly filled by a new gravel bar. Based on the distribution of remnants of the old channel floor and weathered roots of an aspen that appeared to have been exposed before the flood, headward extension of the scour during the flood may have been as much as 125 ft (38.1 m). The gravel bars deposited by tributary 3 have a more limited distribution than the scours. The largest bar had a maximum thickness of 1½ ft (0.5 m), was 20-30 ft (6-9 m) wide, and nearly 100 ft (30 m) long (fig. 19*C*).

BRIGHT ANGEL CREEK BASIN

On the Kaibab Plateau, the flow, erosion, and slumping that resulted from the flood of December 1966 were most noticeable in Thompson and Outlet Canyons—the main tributaries to Bright Angel Creek. The main stem of Bright Angel Creek, however, drains only a few square miles on the plateau and had only small amounts of flow and erosion (table 2).

Before the middle 1930's, open scours were present in places along the drainages in Bright Angel Creek basin. Erosion control—which consisted mainly of filling the scours with rock aggregate—was attempted by the Civilian Conservation Corps in Thompson Canyon, and some of the fills were exposed by the 1966 flood. By 1966, most of the scours and gullies in the Bright Angel basin were covered by a dense mat of grass, which suggests that the scours in Thompson Canyon may have healed naturally without the manmade controls.

THOMPSON CANYON DRAINAGE

Thompson Canyon drains most of the north rim of the Grand Canyon. Most of the flow in Thompson Canyon during the flood of December 1966 came from the southern part of the drainage area and from Fuller Canyon—the main tributary to Thompson Canyon. The grassy floors of the Thompson Canyon basin upstream from site 29 (pl. 1) do not show appreciable recent erosion from runoff. Thompson Canyon tributary 1, which enters Thompson Canyon at site 29, had a flow more than 1 ft (0.3 m) deep, which was sufficient to cause new but minor scouring and the deposition of gravel.

In the reach of Thompson Canyon downstream from site 29 and upstream from tributary 2, scours eroded during the flood of December 1966 had a maximum length of 25 ft (7.6 m) and were not more than 1 ft (0.3 m) deep; most were about ½ ft (0.2 m) deep. Both sides of Thompson Canyon contributed to the floodflow, as shown by a few small scours along the tributaries and by two small debris slides. The slide at location A (pl. 1) partly blocked the main highway. The east-flowing Thompson Canyon tributary 2 was a major contributor to the floodflow and caused gullying. At the mouth of tributary 2, a gully 5 ft (1.5 m) deep and 60 ft (18 m) long was formed along the stream that drains Thompson Canyon; from there, a narrow gully about 4 ft (1.2 m) wide and 5 ft (1.5 m) deep extended about 200

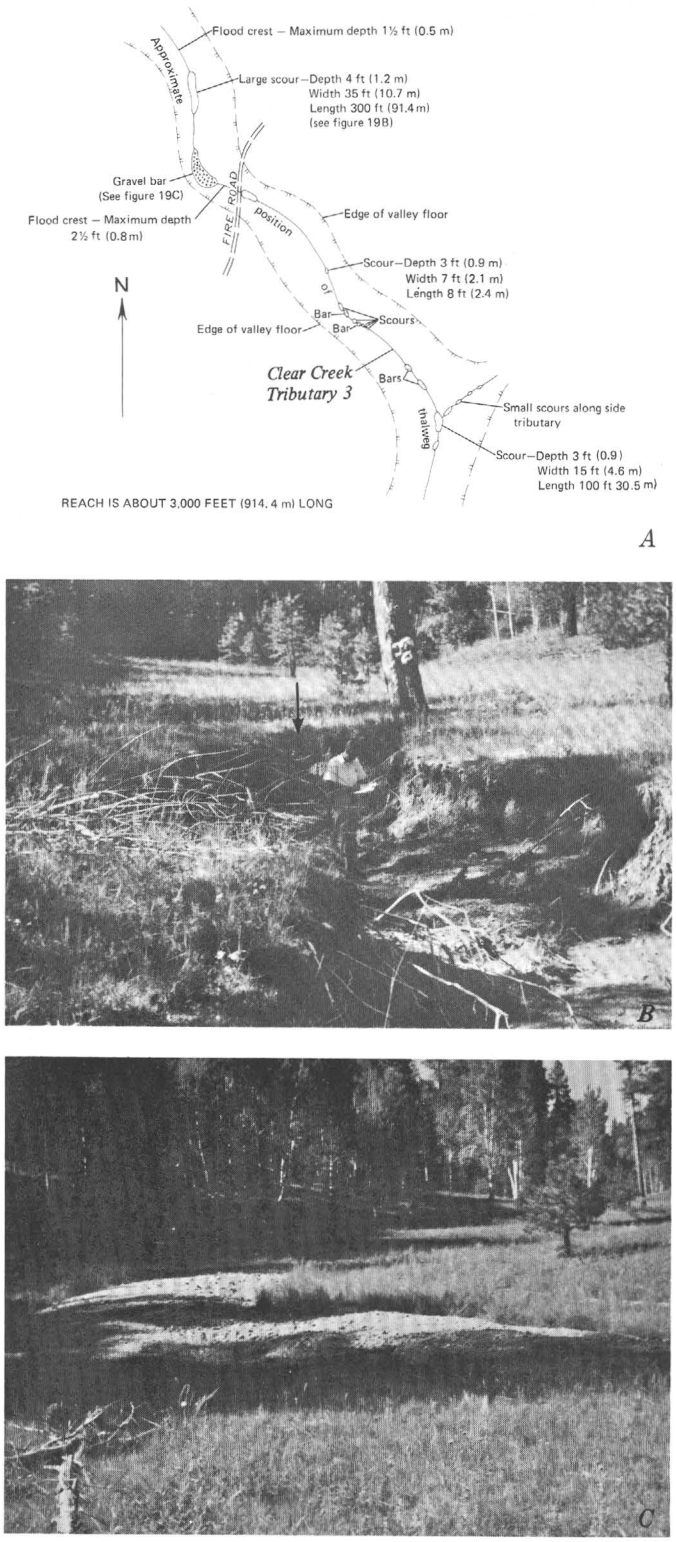


FIGURE 19.—Effects of the flood of December 1966 along Clear Creek tributary 3, Walhalla Plateau. *A*, Diagrammatic sketch of part of Clear Creek tributary 3 showing scours and bars. *B*, Head of the 300-ft-long (90-m-long) scour in Clear Creek tributary 3, which probably was being eroded prior to the flood. Upstream from the headcut (arrow), the valley was not eroded during the flood. *C*, Gravel bar deposited downstream from the 300-ft-long (90-m-long) scour.

ft (60 m) upstream along the tributary and terminated at an outcrop of the Kaibab Limestone. About midway along the tributary gully, part of an older gully, which was filled by rock emplaced by the Civilian Conservation Corps in the 1930's to check erosion, was exposed during the flood. Except for two large scours, only shallow scours and small bars interrupt the continuity of the streambed of Thompson Canyon between tributary 2 and Harvey Meadow. One scour, which was excavated at a change in gradient of the canyon (pl. 1, loc. B), is 2 ft (0.6 m) deep, 4 ft (1.2 m) wide, and 20 ft (6 m) long and exposes part of an old rock-filled channel. The other scour is more spectacular—4 ft (1.2 m) deep, 15 ft (4.6 m) wide, and 40 ft (12 m) long—and was carved along the paved highway a short distance downstream from the mouth of Fuller Canyon.

On the grassy floor of Fuller Canyon, only a small amount of erosion occurred upstream from location D (pl. 1). At location D, the effects of floodwater from the small east-flowing tributaries can be seen readily; some preflood gullies 1–3 ft (0.3–0.9 m) deep were extended headward about 1 ft (0.3 m) but were hardly deepened. Near location E (pl. 1), erosion was slightly more severe, and the old channels and gullies were deepened as much as ½ ft (0.2 m). Although runoff was received from both sides of Fuller Canyon downstream from Blondy Jensen Spring, substantial flow came from the northwest-flowing tributaries near the spring. Near location F (pl. 1), renewed cutting deepened an old arroyo about 0.25 mi (0.4 km) long by as much as 3 ft (0.9 m). (See fig. 20*A*.) Prior to the cutting, the arroyo had a maximum depth of 6 ft (1.8 m) and was stabilized mainly by grass. The amount of headward extension of the arroyo probably was a few tens of feet. Lateral erosion widened the arroyo, and at one place it cut into the shoulder of the Cape Royal–Point Imperial Road. A diamond-shaped gravel fan 1 ft (0.3 m) thick, 150 ft (46 m) long, and 100 ft (30 m) wide was deposited at the downstream terminus of the arroyo (fig. 20*B*) where the gradient is low and the canyon is wide. Between the gravel fan (loc. F) and site 31 (pl. 1), the channel is generally well defined and its lower part forms a ditch along the south side of the Cape Royal–Point Imperial Road. The average deep-

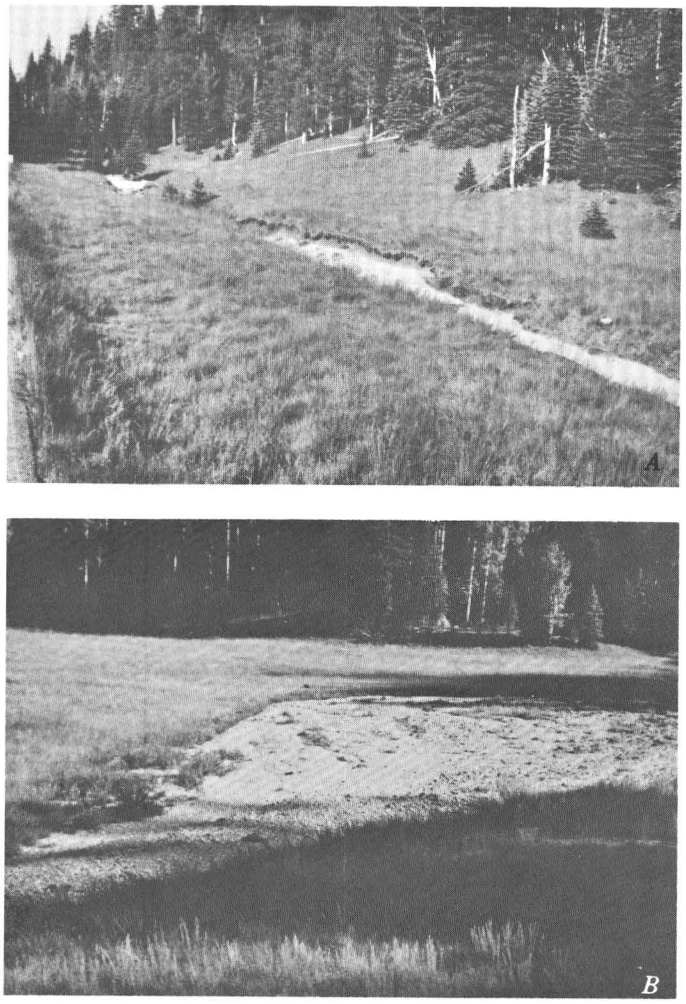


FIGURE 20.—Effects of the flood of December 1966 in Fuller Canyon, Kaibab Plateau. Fuller Canyon has a wide grass-covered floor which is bordered by a forest of pine, spruce, and some aspen. *A*, An old arroyo in Fuller Canyon that was deepened and slightly widened by the flood. *B*, A diamond-shaped gravel fan that was deposited at the downstream terminus of the arroyo. The gravel fan is 150 ft (46 m) long and 100 ft (30 m) wide and is the largest single deposit of gravel on the Kaibab Plateau.

ening of the ditch was about 1 ft (0.3 m). Near the mouth of Fuller Canyon, a 2½-ft-thick (0.8-m-thick) deposit of gravel accumulated at the junction of the main highway to the north rim and the Cape Royal–Point Imperial Road; the deposit is the largest known to have accumulated on the Kaibab Plateau during the flood of December 1966.

Harvey Meadow is a roughly elliptical depression in the widest part of Thompson Canyon (pl. 1). The roadbed of Point Sublime Trail forms a low dam that further accentuates the depression. The flood of 1966 filled the depression and formed a lake about 500 ft (150 m) wide. Although the overflow from the lake crossed the Point Sublime Trail, it caused only minor erosion because the water was spread out over the meadow. A small poorly formed gravel delta accumulated along the edge of the meadow at the northeastern limit of the lake; the delta consists of material transported mainly from Fuller Canyon.

Thompson Canyon, between Harvey Meadow and Bright Angel Spring at the edge of the Kaibab Plateau, is narrow, and in places the canyon floor is only 50 ft (15 m) wide. Upstream from location C (pl.1), the shallow channel and canyon floor are mantled by a thick stand of grass that remained virtually intact during the flood. Location C marks the head of a preflood arroyo that extends upstream from the plateau rim near Bright Angel Spring—a distance of less than 0.50 mi (0.8 km). At its head, the arroyo is 7 ft (2.1 m) deep; downstream it is 5-8 ft (1.5-2.4 m) deep and 8-12 ft (2.4-3.7 m) wide. The head of the arroyo apparently has been stabilized by the roots of a 4½-ft-diameter (1.4-m-diameter) Engelmann spruce. On the upstream side, the roots still partially control headward erosion, but fresh exposures of alluvium indicate that the arroyo was extended headward about 8 ft (2.4 m) and deepened ½ ft (0.2 m).

Near Bright Angel Spring, several debris slides were caused by the flood. One slide from the left bank blocked the preflood arroyo, which may not have been more than about 4 ft (1.2 m) deep prior to the flood. The floodwater was diverted across a relatively flat area of tall dense grass cover, cascaded over a 15-ft-high (4.6-m-high) vertical cut at the downstream edge of the flat area, and then rejoined the main arroyo. During the flood, the vertical cut was extended headward 40 ft (12 m).

OUTLET CANYON DRAINAGE

Outlet Canyon drains an area between the northern boundary of the Grand Canyon National Park and the north rim of the Grand Canyon west of the Thompson Canyon drainage. During the flood of December 1966, a peak flow of 414 ft^3/s (11.7 m^3/s) at site 35 left the north rim through Outlet Canyon and caused substantial channel modification. The floodflow in the 1-mi-long (1.6-km-long) reach of Outlet Canyon near the Point Sublime Trail deposited many gravel bars, cut large scours, and renewed trenching of a continuous arroyo (fig. 21). The number, depth, and size of the scours progressively increase downstream until the scours coalesce to form a continuous inner trench cut below the level of the pre–1966 channel.

Upstream from the Point Sublime Trail near the confluence of Outlet Canyon and tributary 1, the stream channel is 2-3 ft (0.6-0.9 m) deep and 25-60 ft (7.6-18 m) wide. Some of the banks on the outside

FIGURE 21.—Erosion caused by the flood of December 1966 in Outlet Canyon, Kaibab Plateau. Renewed arroyo cutting in Outlet Canyon between a point about 0.50 mi (0.8 km) downstream from the Point Sublime Trail and the edge of the plateau; the cutting deepened the old channel 1–2 ft (0.3–0.6 m).

curves of meanders were accentuated and cut back 1–2 ft (0.3–0.6 m). Many shallow scours about 1 ft (0.3 m) deep were excavated in the grass-floored channel, but only one significant scour—1½ ft (0.5 m) deep, 5 ft (1.5 m) wide, and 70 ft (21 m) long— was noted upstream from the Point Sublime Trail. Scours were cut below several of the 2-ft-high (0.6-m-high) limestone ledges that cross the channel about 1,000 ft (300 m) north of the Point Sublime Trail. Gravel deposits as much as 2 ft (0.6 m) thick were concentrated in diamond-shaped bars between the limestone ledges and the trail, which indicates that much of the detritus transported from the upper reaches of the Outlet Canyon drainage accumulated in this part of the basin.

Between the Point Sublime Trail and the point where the newly formed continuous arroyo begins (pl. 1), deeply scoured reaches alternate with those having bars or shallow scours. Many of the scours are 3 ft (0.9 m) deep, 10 ft (3 m) wide, and 50–60 ft (15–18 m) long; one has a maximum relief of 5 ft (1.5 m) between its base and the top of a nearby gravel bar. Gravel bars between the scours are as much as 2 ft (0.6 m) thick and 50 ft (15 m) long. Spotty lateral cutting adjacent to the gravel bars removed from 2 to 3 ft (0.6 to 0.9 m) of alluvium from the sides of the channel. In places sheets or bars of silty sand nearly 1 ft (0.3 m) thick were deposited along the lower slopes of the channel. In general, the channel sides were only slightly affected by the flood of 1966, but between 50 and 75 percent of the channel bottom was modified by scours or bars.

The reach of Outlet Canyon 0.5 mi (0.8 km) downstream from the Point Sublime Trail was more severely dissected than any other drainage on the Kaibab Plateau (fig. 21). Remnants of the pre-1966 grass-covered channel floor outline a low bench 1–3 ft (0.3–0.9 m) high along one or both sides of the new channel. Gravel bars were deposited downstream from large scours in the new channel and in places along the inside curves of meanders. Although the flood eroded about 75 percent of the channel floor, about 50 percent of the preflood channel sides was left intact.

CRYSTAL CREEK BASIN

Crystal Creek drains only a small part of the Kaibab Plateau. The creek and its tributaries are in shallow canyons that have alluvial floors. Milk Creek tributary, where crossed by the Point Sublime Trail, passes through a small meadow that has an undulating surface caused by grass-covered dolinen formed in the Kaibab Limestone. The floodflow, upon entering the meadow, fanned out and inundated the dolinen and the Point Sublime Trail. As indicated by debris, a temporary lake about 8 ft (2.4 m) deep and 200 ft (60 m) wide was formed. The flow that entered the lake deposited a 2-ft-thick (0.6-m-thick) gravel delta over a 40- by 30-ft (12- by 9-m) area. Along the Point Sublime Trail about 0.10 mi (0.16 km) east of Milk Creek tributary, the flood caused or greatly accentuated the subsidence of a sinkhole in the alluvium. The sinkhole—a nearly vertical-walled depression 10 ft (3 m) wide, 40 ft (12 m) long, and 7 ft (2.1 m) deep—extends across a stream channel and now (1967) can intercept all the flow of the tributary.

OTHER AREAS

The flood of December 1966 produced relatively minor effects in all other drainage basins on the Kaibab Plateau. The broad undissected meadows in northern Del Motte Park, upper North Canyon, the lower part of Lookout Canyon, Dry Park, and Pleasant Valley show no evidence of recent floods; however, the flood of 1966 caused some damage in Kanabownits Canyon (table 2).

Evidence of recent erosion as a result of floods prior to those of 1966 is recognizable in several isolated places on the Kaibab Plateau. In the southern part of Del Motte Park and in upper Little Park several shallow discontinuous gullies eroded before December 1966 mar the gentle undulating surface of the parks. The gullies are 2–3 ft (0.6–0.9 m) deep, as much as 30 ft (9 m) wide, and some are a few hundred feet long. A discontinuous arroyo in Tipover Canyon is as much as 6 ft (1.8 m) deep, is generally less than 8 ft (2.4 m) wide, and has sharp banks covered by a scattered stand of grass. A 3½–4-ft-deep (1.1–1.2-m-deep) arroyo extends from near the confluence of Quaking Aspen and Browns Canyons to the rim of the Kaibab Plateau. Another arroyo, which is 3–5 ft (0.9–1.5 m) deep, is present in the lowermost 0.50 mi (0.8 km) of a tributary that enters Quaking Aspen Canyon about 2 mi (3 km) upstream from the mouth of Browns Canyon (pl. 1). Between the two arroyos in Quaking Aspen Canyon, several small sinks or depressions intercept all the small flows. Although grass is growing on the sides and bottoms of the sinks, the heads of some are being eroded. Farther north in parts of Dry Park, short narrow arroyos about 2 ft (0.6 m) deep have been trenched along an old wagon road.

RELATION OF SCOURING TO FLOOD DEPTH

During the flood of December 1966, different amounts of scouring took place along the drainages on the Kaibab Plateau. Integration of the scours caused deepening of the channel or renewed arroyo cutting mainly along parts of Outlet Canyon and Walhalla Glades. Outlet Canyon had the most cutting. The renewed arroyo cutting in the two drainages was the result of large flows that probably were continuous for 2 or 3 days. The renewed cutting occurred by extension and integration of scours rather than by headward migration of a single knickpoint. For example, in Outlet Canyon the scours are larger and more closely spaced near the upstream end of the new arroyo than they are in reaches farther upstream.

As shown in the following tabulation, there is a rough relation between the amount of scouring that occurred during the flood and the maximum depth of the flood crest. The dense grass cover and the alluvium and soil were similar in all the drainages; the grass almost covered the channels, old scours, and valley or canyon floors. For flood depths of 1½–3 ft (0.5–0.9 m), the depth of the scours usually is 1–3 ft (0.3–0.9 m) below the bottom of the channels or valley floors not having a well-defined channel. The deepest and largest scours—nearly 5 ft (1.5 m) deep—were formed along Outlet Canyon by flood depths of 4–5 ft (1.2–1.5 m).

Amount of scouring	*Maximum depth of flood crest (ft)*
A few inches of soil was removed locally in channels, which exposed roots of grass and other plants. Almost no erosion on valley floors not having channels	<½
A few small scours formed in the channels. Locally, grass roots were exposed on the valley floors not having channels	½–1
Depends on the depth: Some lateral cutting and scours common in channel. Few to many scours formed on valley floors not having channels. Renewed arroyo cutting occurred in a short reach of Walhalla Glades and Outlet Canyon	>1

EFFECTS OF FLOODS IN THE TRIBUTARY GORGES OF GRAND CANYON—FLOOD OF DECEMBER 1966 AND PREVIOUS RECENT FLOODS

The tributary gorges in eastern Grand Canyon that show channel modification as a result of the 1966 flood include those from Nankoweap Creek to Deer Creek along the southern margin of the Kaibab Plateau (tables 2, 3). Little flow occurred in the side gorges that drain the south rim of the Grand Canyon. The channels in the gorges are lined with gravelly alluvium except where consolidated rocks are exposed in the narrow parts of the gorges. The gravelly alluvium comprises multiple-fill terraces—irregular alluvial terraces of local extent—that have levels ranging from 2 to 50 ft (0.6 to 15 m) above the streambeds. Most of the terraces are 4–6, 8–10, 12–15, and 20–30 ft (1.2–1.8, 2.4–3.0, 3.7–4.6, and 6–9 m) high. Some of the drainages, such as Bright Angel Creek, have only one well-defined terrace level, which is between 5 and 7 ft (1.5 and 2.1 m) high. Many of the terraces contain accumulations of large boulders, which account for some of the irregularity in their heights. Some of the boulder accumulations are the result of past mudflow activity. Along several drainages (pl. 1), older alluvial fill deposits—called the reddish-brown unit—have been eroded into terraces higher than the multiple-fill terraces. In the Nankoweap and Chuar Creek basins, terraces of the reddish-brown unit are more than 100 ft (30 m) above the streambeds (Springorum, 1965).

Many multiple-fill terraces less than 8 ft (2.4 m) above the streambeds are inundated by large floods. Below this level, there may be as many as three terraces; however, generally only one or two are present at levels of 2–3 or 4–5 ft (0.6–0.9 or 1.2–1.5 m) above most streambeds. In the north rim area many low terraces were covered by floodwater during the flood. Along some drainages, such as Crystal, Dragon, Lava, and Nankoweap Creeks, terraces higher than 8 ft (2.4 m) above the streambeds were inundated and were modified by the mudflows. Cottonwoods and junipers growing on the low terraces and large bars in the stream channels and on the channel floor help substantiate that, with few exceptions, only minor changes in channel depth resulted from the flood of 1966. Mature junipers growing within a few feet of the bottoms of the channels also indicate that little change in channel depth has occurred during the last few centuries.

A striking effect of the flood of December 1966 was the movement of mud, rocks, and logs as mudflows and debris slides in the side gorges of Marble and Grand Canyons—principally in the Nankoweap, Chuar, Crystal, and Shinumo Creek drainage basins (pl. 1). The

TABLE 3.—*Brief descriptions of the flood of December 1966 and previous floods in the tributary gorges of the Grand Canyon*

Tributary	Brief description of flood of December 1966	Evidence of previous floods
Saddle Canyon	Moderate flow; minor scouring of channel.	No information available.
Nankoweap Creek	One of the rare large floods along this creek; channel was severely modified; mudflows occurred only in the upper reaches of the watershed.	The flood of 1966 removed traces of previous floods.
Kwagunt Creek	A large flood but probably one of rather common occurrence; moderate scouring of the channel.	Based on the relation of the 1966 flood peak to the low terrace, older floods have been considerably larger.
Chuar Creek	One of the major floods in Lava Creek and Chuar Creek below Lava Creek; a mudflow extended from the head of Natchi Canyon downstream along Lava and Chuar Creeks to the Colorado River; severe to moderate modification of the channel affected by mudflow and accompanying streamflow; the channel of Chuar Creek above its confluence with Lava Creek carried only a minor amount of flow.	Debris from a previous large flood is present near the confluence of Lava and Chuar Creeks.
Unkar Creek	Rather small flow; channel shows only minor effects from flooding.	Low terraces indicate previous floods much larger than the flood of 1966.
Clear Creek	Large flow; considerable lateral cutting and scouring; lateral cutting removed about half of a mescal pit used by the Pueblo Indians about A.D. 1050–1150.	No information available.
Bright Angel Creek	Flood peak was the second highest of record; volume of flow was the largest recorded since monitoring of the creek began in 1922; major modification and scouring of channel; flood channel cut through terrace at Phantom Ranch and removed terraces upstream from Phantom Ranch; a mudflow probably occurred in the upper reach; the tourist trail, campgrounds, pipeline, and a few buildings were damaged.	Flood peak of 1936 is the highest of record; the flood caused only moderate channel scouring.
Crystal Creek	Flood consisted of streamflow and mudflow stages; mudflow covered some of the terraces and destroyed an archeological site used about A.D. 1050–1150; major modification of the channel included scouring, deepening, and some deposition; deposition of large boulders at mouth of creek; very little flow from Crystal Creek above Dragon Creek.	Flood of 1966 removed all evidence of previous floods in reaches of Milk, Dragon, and Crystal Creeks traversed by mudflow.
Tuna Creek	Small flow; minor effect on channel.	A large flood a few years before 1966 removed vegetation and loose rocks from channel.
Shinumo Creek	Large flow; considerable scouring in places in the channel; several mudflows in upper part of watershed; probably one of the highest flows since 1890.	No information available on higher floods.
Tapeats Creek	Small flow; essentially no effects on channel.	Wood debris and drift from larger floods in channel; evidence of an old mudflow probably formed during the flood of 1961 covers parts of terraces.
Deer Creek	Moderate flow; minor scouring in channel.	None.

mudflows in the Crystal and Chuar Creek drainage basins extended to the Colorado River; at least nine others flowed more than 0.5 mi (0.8 km). These are the first mudflows reported in the Grand Canyon, although an older mudflow was recognized along Tapeats Creek during this investigation.

Evidence that mudflows were a major part of the floods of 1966 in Natchi-Lava-Chuar, Milk-Dragon-Crystal, and other drainages includes the following:

(1) An aggregate of mud, sand, and small pebbles was plastered on the sides of stream channels in many places (fig. 22).

(2) In the reaches having mudflows, preflood gravel bars, low terraces, and other features were largely obliterated.

(3) Differences in elevation are more than 12 ft (3.7 m) between the highest mudmarks on the opposite sides of the channel of Dragon Creek—less along others—where the distance between the mudmarks is only about 150 ft (46 m).

(4) Pebbles were transported as suspended sediment and were deposited on large boulders (fig. 22). The

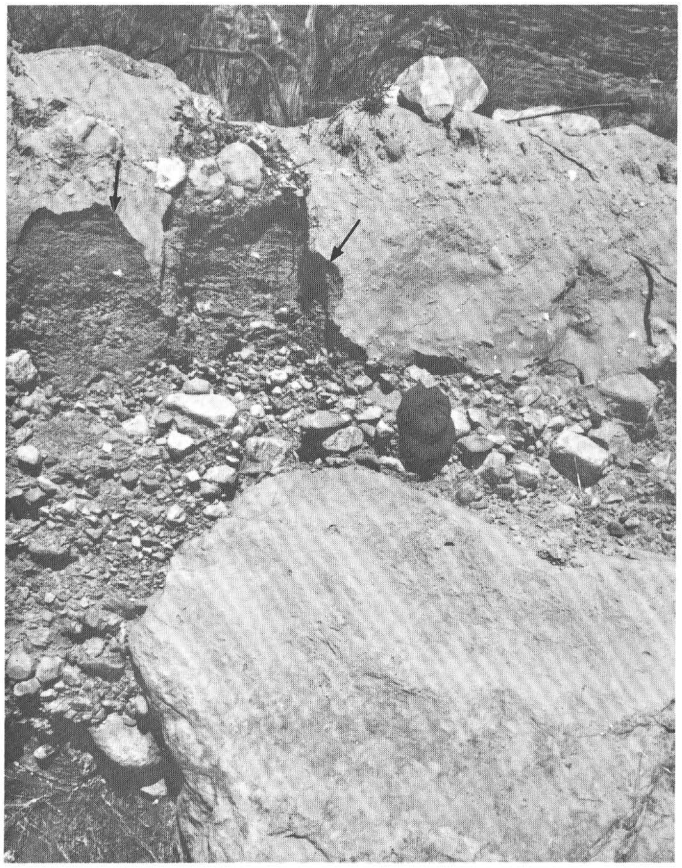


FIGURE 22.—Debris deposited by mudflows in Hindu Amphitheater and Natchi Canyon. Muddy debris plastered by the mudflow along the channel of Dragon Creek in Hindu Amphitheater is as much as 3 in. (76 mm) thick, where it has not been removed (arrows) by subsequent streamflow.

boulders are positioned more than 20 ft (6 m) from the nearest bank, as indicated by the mudmarks that outline the peak of the flow.

(5) Silt, sand, and small pebbles were plastered on tree trunks and limbs and on logs that were transported and deposited at the highest level attained by the flood.

(6) Fine plant debris is generally absent along the mudline.

(7) Remnants of lobes of muddy material were formed along the borders of the areas affected by the floods (figs. 22, 23).

(8) At the confluence of Milk and Dragon Creeks, muddy material from Milk Creek flowed over the low divide between the two creeks and accumulated along the bank of Dragon Creek above its floodline.

The flood of 1966 also caused at least 80 debris slides or debris avalanches in the area between Saddle Canyon and Shinumo Creek (pl. 1; fig. 24). This is the greatest number of debris slides known to have occurred in this area during a single storm in the 20th century.

Most of the debris slides originated on the Hermit Shale or on the upper part of the Supai Formation. As indicated by the bedrock exposed in the scarred areas, the slides generally picked up additional detritus en route down the steep Supai slopes and came to rest in the bottoms of the canyons, where most of the material was carried downstream by floodwater. In many places the only evidence of a debris slide is the fresh scar left by the jumbled mass of material as it cascaded down the steep slopes. In other places muddy debris formed small, rounded, partially lobate, discontinuous ridges along the borders of the slide area or in the bottoms of the canyons at the terminus of the slide.

The flood of 1966 was not the first to cause debris slides and mudflows in the eastern Grand Canyon area in the 20th century. An older mudflow, which may have occurred in 1961, was recognized along Tapeats Creek; a few debris slides formed prior to the flood of 1966 were noted near the mouth of Deer Creek, and boulder deposits along Crystal Creek upstream from Dragon Creek indicate a relatively old mudflow along that drainage (pl. 1). Other scars caused by debris slides that formed before 1966 are present in the heads of most of the side gorges. Many slides cannot be seen readily except from the air. The scars are in different stages of healing and indicate that in past decades or centuries debris slides have been rather common along the north rim of the Grand Canyon. Past mudflow activity must have been more common than generally recognized in the eastern Grand Canyon because (1) many debris slides, which have scars partly healed by vegetation, are apparent along the north rim escarpment and (2) accumulations of large boulders at the mouths of Unkar and Bright Angel Creeks, Fossil Canyon, and other drainages are similar in appearance to those deposited by the 1966 mudflow at the mouth of Crystal Creek.

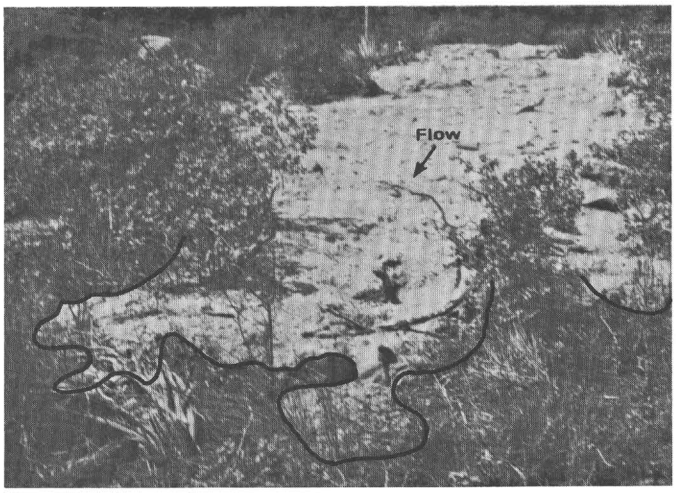


FIGURE 23.—Lobes of the light-colored mudflow that terminate (solid line) in the vegetation on a low terrace in Natchi Canyon. The mudflow was a few inches thick and moved in the direction of the arrow.

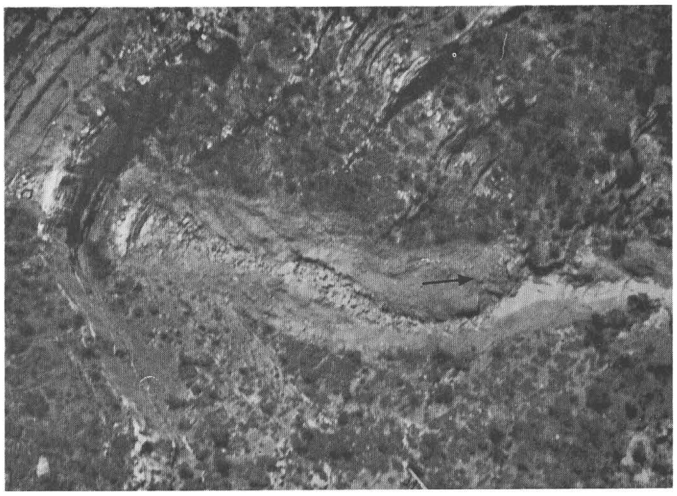


FIGURE 24.—Scar of the main mudflow-debris slide that contributed much debris to the mudflow in Natchi Canyon. Aerial view. Direction of movement (arrow) was from left to right over the almost vertical cliff at left edge of photograph.

NANKOWEAP CREEK BASIN

The Nankoweap Creek basin heads in steep-walled amphitheaters, which received large amounts of precipitation during the storm of December 1966 (pl. 1). In two amphitheaters—one on the trunk Nankoweap Creek and the other on a tributary south of Brady Peak—the debris slides were sufficiently fluid to form true mudflows that moved short distances downstream along the canyon floors. The mudflow south of Brady Peak probably was derived from four main slides and extended nearly 0.5 mi (0.8 km) downstream (pl. 1). The mudflow along Nankoweap Creek originated from two slides and extended about 1 mi (1.6 km) downstream. The channels in which these mudflows occurred tend to be straighter than those unmodified by mudflows; they now occupy sharply defined notches 8–10 ft (2.4–3.0 m) deep. The amount of channel deepening is not easily discernible but appears to have been from 1 to 4 ft (0.3 to 1.2 m).

Downstream from the reaches affected by the mudflows, the channel of Nankoweap Creek progressively widens and reaches its maximum width in the area northwest of Nankoweap Butte, where the creek and its major tributaries are bordered by well-developed gravel terraces as much as 100 ft (30 m) high (pl. 1). Farther downstream, the creek flows through narrow Nankoweap Canyon before it empties into the Colorado River. Although much channel modification occurred in the reaches north of Nankoweap Butte and at the mouth of Nankoweap Creek, no appreciable downcutting or aggradation occurred in Nankoweap Canyon as a result of the flood.

The channel of Nankoweap Creek north of Nan-

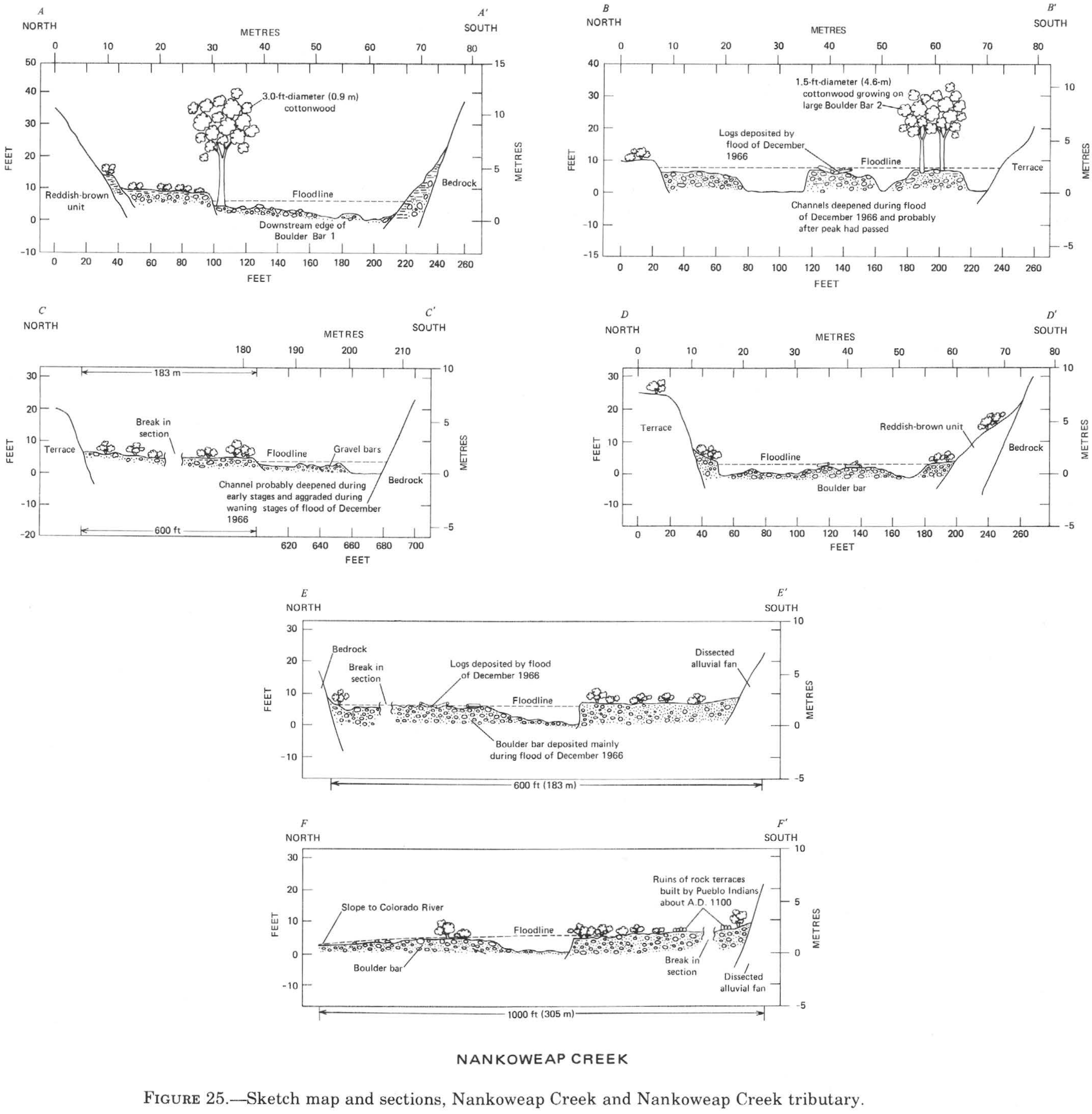


FIGURE 25.—Sketch map and sections, Nankoweap Creek and Nankoweap Creek tributary.

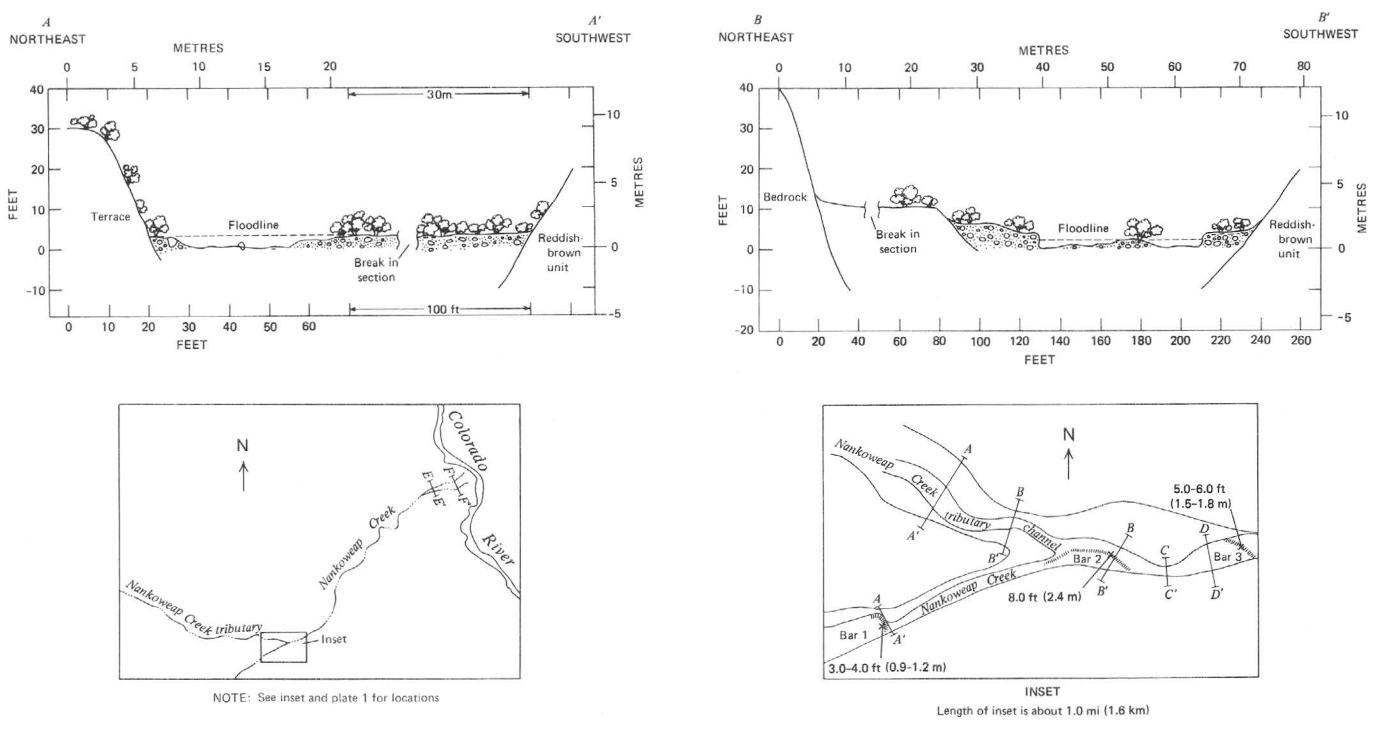
koweap Butte contains large gravel bars that extend across the channel and give the creek a stepped profile (figs. 3, 25, 26). Each bar consists of gravel deposits dissected by floodwater channels as much as 3 ft (0.9 m) deep and 20 ft (6 m) wide (fig. 26). The bars are relatively stable as shown by the scattered cottonwoods and brushy plants. Logs and other recent flood debris indicate that the bars were covered by the flood of 1966 (fig. 25, section *B–B′*). The downstream ends of the bars are well defined and have a relief of between 2 and 8 ft (0.6–2.4 m). (See fig. 26*A*.) During the flood of 1966 and previous floods, the main channel shifted laterally along many of the snouts of the bars and caused considerable cutting, which may account for much of the high relief at the downstream ends of the bars.

Nankoweap Creek has built a rather large alluvial fan into the channel of the Colorado River. Remnants of older alluvial fans are present on both sides of the creek near the river (pl.1). As a result of the flood of December 1966, Nankoweap Creek deposited a small fan of pebbles to small boulders in the Colorado River along the upstream side of the older alluvial fans. The new fan extends about 150 ft (46 m) into the river and is about 300 ft (90 m) wide. The building of this and older alluvial fans has confined the channel of the Colorado River to its left bank, where its low-water channel is about 100 ft (30 m) wide. The detritus from the 1966 flood caused only a narrowing of the river channel and did not change the configuration of Nankoweap Rapids.

Effects of the deposition during the flood of 1966 are apparent for about 0.75 mi (1.2 km) upstream along Nankoweap Creek, where gravel-bar accumulations attain heights of about 6 ft (2 m) above the streambed. The south side of the channel of Nankoweap Creek is cut into a 5-7-ft-high (1.5-2.1-m-high) gravel terrace. Rock walls or terraced plots, which probably were built by the Pueblo Indians, are present along the top of the terrace. At section *E–E′* (fig. 25) the crest of the flood was about 1 ft (0.3 m) below this terrace. Downstream at section *F–F′* (fig. 25), where the terrace is slightly lower in relation to the streambed, water inundated the low parts of the terrace but did not cover the terraced plots built by the Pueblo Indians. The relation of the floodline to the terraced plots indicates that the flood of 1966 was one of the largest that has occurred in Nankoweap Creek.

KWAGUNT CREEK BASIN

Kwagunt Creek drains a narrow watershed between the larger Nankoweap and Chuar Creek drainages. Although the peak flow of 1966 was large (table 2), the amount of channel damage was rather moderate. The low-water channel of Kwagunt Creek was smoothed and straightened. At sections *A–A′* and *B–B′* (fig. 27), the channel was not deepened appreciably by the flood, but fresh scars, which are generally less than 4 ft (1.2 m) wide, were cut along the sides and into the



NANKOWEAP CREEK TRIBUTARY

FIGURE 25.—Continued.

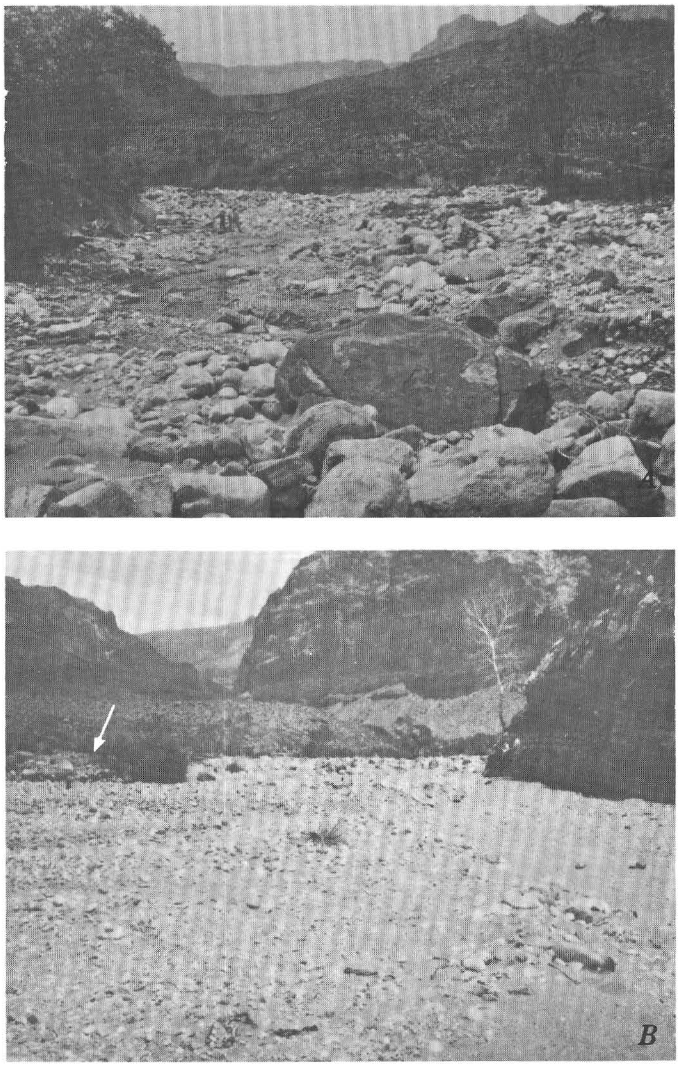


FIGURE 26.—Gravel-floored channel of Nankoweap Creek near site 15 after the flood of December 1966. *A*, Looking upstream along Nankoweap Creek across section *A–A′*. (See fig. 25.) View is from small gravel bar upstream from gravel bar 2 to the lower end of gravel bar 1, where the three men are standing, approximately along section *A–A′*. *B*, Looking downstream along Nankoweap Creek. The narrow channel at section *C–C′* in figure 25 is in the center of the picture and is where the peak of the flood of December 1966 was 3½–4 ft (1.1–1.2 m) above the present channel. The low 5-ft-high (1.5-m-high) terrace (arrow) in the left-center of the photograph was not inundated. During the flood peak, the channel at section *C–C′* apparently was deepened and was filled by pebble- to small-cobble-size material during the declining stage of the flood.

bottom of the channel. The depth of the channel has been nearly stable during the last century or possibly longer, as indicated by the root-crown positions of the 2-ft-diameter (0.6-m-diameter) junipers that are less than 2 ft (0.6 m) above the present streambed. The flood of 1966 inundated only the lowest—2–4 ft (0.6–1.2 m) above the streambed—of multiple-fill terraces (fig. 27, sec. *A–A′*). Debris transported during the flood accumulated as a small gravel fan at the mouth of Kwagunt Creek. The fan protrudes between 50 and 75 ft (15 and 23 m) into the Colorado River and is about 125 ft (38 m) wide along the shoreline.

CHUAR CREEK BASIN

The Chuar Creek drainage was more affected by the flood of December 1966 than any of the drainages eastward from the Kaibab and Walhalla Plateaus. The greatest amount of channel modification was in Natchi Canyon, where the principal mudflow originated, and along Lava Creek.

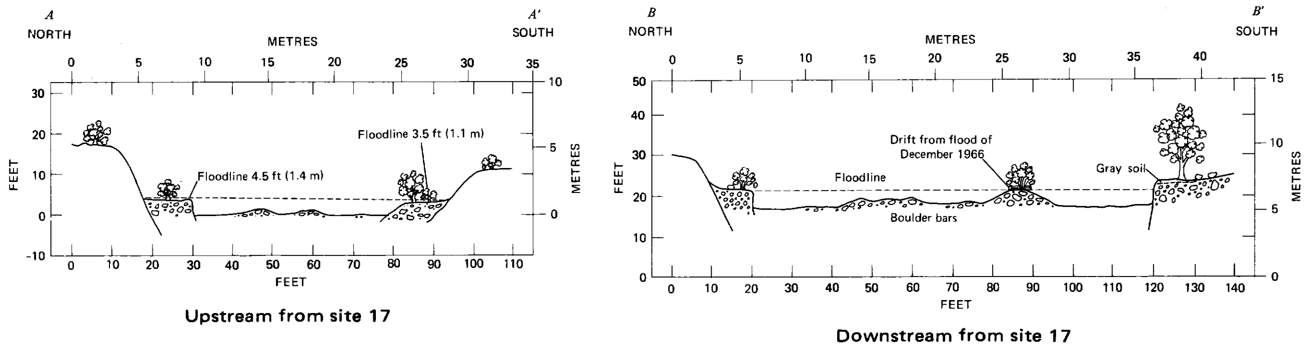
HEADWATERS AREA

Several debris slides joined to form mudflows in the headwaters of Lava Creek and Natchi Canyon. The principal mudflow originated southwest of Naji Point in Natchi Canyon. At least part of the mudflow was rather viscous, as shown by mounds of mud still remaining at the bases of the cliffs; however, most of the muddy debris entered the channel of the trunk stream that drains Natchi Canyon and continued downstream along Lava and Chuar Creeks to the Colorado River. Near the head of Lava Creek, a viscous mudflow (pl. 1), which was smaller but similar to the one in Kanab Canyon (see the section entitled "Mudflow at the Mouth of Kanab Canyon"), accumulated debris as an elongate mound at the base of the canyon wall.

CONFLUENCE OF NATCHI CANYON AND LAVA CREEK

The channels of the trunk stream in Natchi Canyon and Lava Creek were studied on the ground at their area of confluence south of Poston Butte. In Natchi Canyon above the confluence, muddy debris accumulated on the lower terraces that line the channel and was plastered on trees and large rocks as much as 16 ft (4.9 m) above the streambed. Near sections *A–A′* and *B–B′* in figure 28, the lower boundary of the mudmarks is less than 2 ft (0.6 m) above the present (1967) streambed, which suggests that little deepening of the channel could have occurred after the mudflow. In one place 3½ ft (1.1 m) above the streambed, the mudflow did not remove the litter that had accumulated under a 2-ft-diameter (0.6-m-diameter) juniper. In other places, however, large scours were gouged in the channel, particularly downstream from large boulders.

Near sections *A–A′* and *B–B′* in figure 28, differences in the height of the mudmarks are about 2 ft (0.6 m) on opposite sides of the channel. By the time the mudflow reached this area, it was more fluid than it was in the upstream reach, where differences in the height of the mudlines on opposite sides of the channel were greater. The mudflow deposited a thin mantle of



KWAGUNT CREEK

FIGURE 27.—Sections along Kwagunt Creek near site 17.

debris where it spread out on the terraces (fig. 23). The mudflow was moderately fluid and formed a few ridges and lobes as it moved rather uniformly around rocks and vegetation without bending many of the plants.

The flood of December 1966 caused considerable change in the wide part of the canyon that extends 0.25 mi (0.4 km) downstream from the confluence of Natchi Canyon and Lava Creek. The area contained a swamp and supported a heavy growth of reeds and similar vegetation when it was visited by R.C. Euler in the summer of 1966. Coarse gravel bars, which have a maximum relief of 6 ft (1.8 m) deposited by the flood of December 1966 obliterated the swamp (fig. 29*A*). Along section *D–D'* (fig. 28) root crowns of 1–2-ft-diameter (0.3–0.6-m-diameter) cottonwoods are estimated to be buried 2 ft (0.6 m) below the present (1967) stream channel.

In section *D–D'* (fig. 28) the mudline is slightly above the top of the gravel bars and is only 7 ft (2.1 m) above the present streambed. A short distance downstream from section *D–D'*, mudmarks are not visible along the sides of the channel because the marks left by the mudflow were buried beneath the gravel deposits; therefore, considerable streamflow and gravel deposition apparently occurred after the mudflow. The gravel forms a large bar; the downstream end of the bar is between sections *D–D'* and *E–E'* (fig. 28). At its terminus, the bar is 125 ft (38 m) wide and 10 ft (3 m) high. Natchi Spring now issues from the downstream end of the bar and heads a short reach of perennial streamflow. At the time of Euler's visit in the summer of 1966, the perennial streamflow extended upstream to about the junction of Natchi Canyon and Lava Creek.

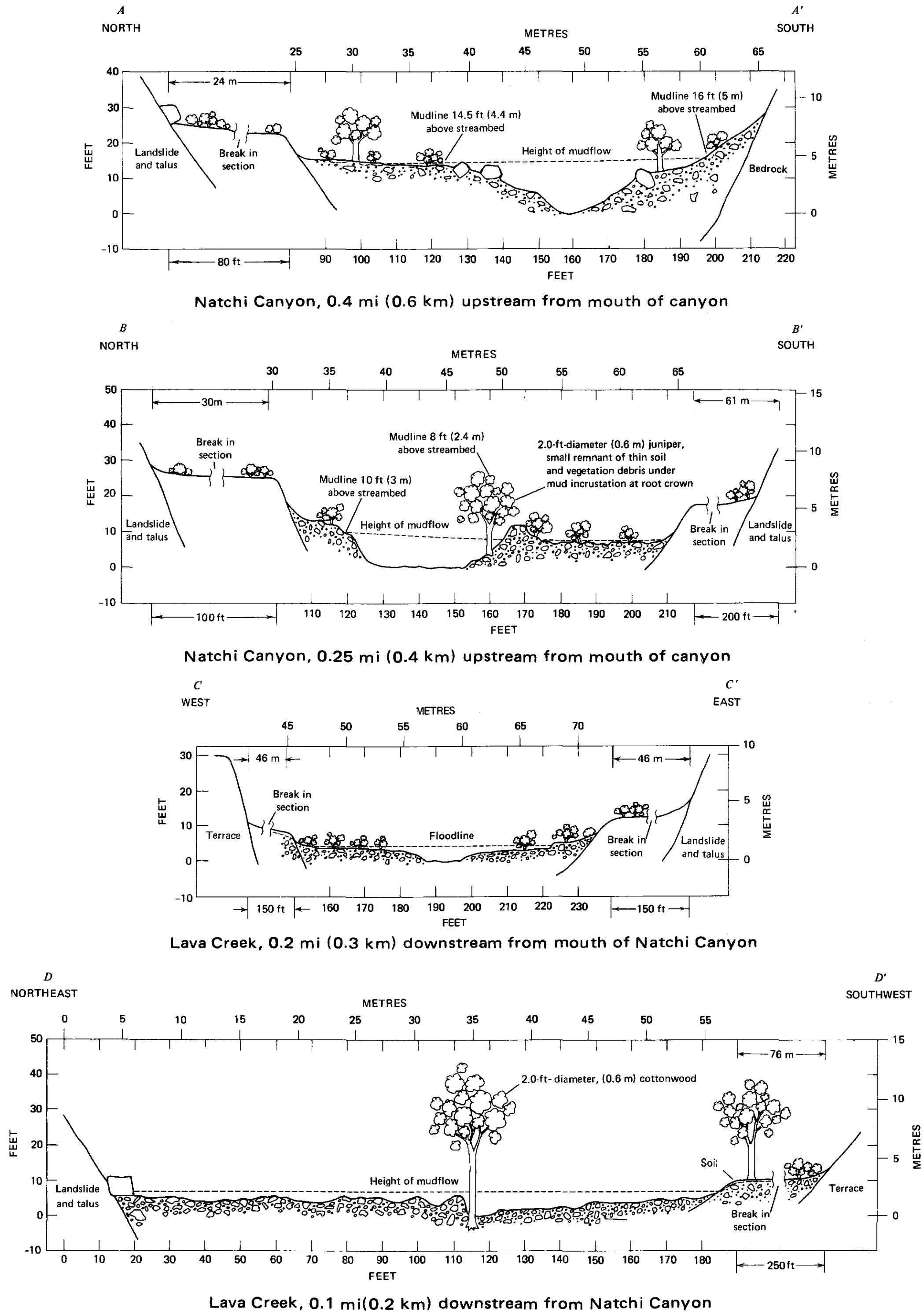
LAVA CREEK, SITE 21

At site 21 between Natchi Canyon and Chuar Valley (pl. 1; fig. 29*B*), large boulders have lodged together and form barriers that drop off 5–10 ft (1.5–3.0 m) on the downstream side and give the longitudinal profile of Lava Creek a step appearance. The flood accentuated the drops by removing all the loose material and brush. In a relatively straight reach of the channel within 100 ft (30 m) upstream and downstream from one of these barriers, the mudline was 6 ft (1.8 m) above the streambed and barely above a 5–6-ft-high (1.5–1.8-m-high) terrace. A minimum flow depth of 3 ft (0.9 m) occurred at the crest of the barrier, and a maximum flow depth of 9 ft (2.7 m) occurred at the lower side of the barrier where scouring took place. Generally, the scours were 2–3 ft (0.6–0.9 m) deep, but some scours were as much as 5 ft (1.5 m) deep. Lateral cutting was generally less than 2 ft (0.6 m), although in places the channel was widened by as much as 6 ft (1.8 m). The small deposits of vegetal debris at the edges of the flow indicate that the mudflow was much more fluid here than it was near the mouth of Natchi Canyon.

CHUAR VALLEY

Near the confluence of Lava and Chuar Creeks in Chuar Valley, the valley floor is generally more than 150 ft (46 m) wide. The channel is braided and contains broad 3–5-ft-high (0.9–1.5-m-high) gravel bars (fig. 29*C* and *D*) that were deposited by the flood of 1966 and previous floods. A short distance downstream from section *F–F'* (fig. 28), marks from mud and debris extend only 3 ft (0.9 m) above root crowns of 4-ft-diameter (1.2-m-diameter) cottonwoods that are at the level of the present (1967) streambed. Generally, less than 2 ft (0.6 m) of lateral cutting took place along the sharp bends and meanders. The sharp bends and some of the large preflood boulder bars formed barriers and diverted the mudflow around low areas and over some terraces and other large bars. About 0.25 mi (0.4 km) downstream from the confluence of Lava and Chuar Creeks, where Chuar Creek makes several tight bends, the mudflow left marks that are as much as 4 ft (1.2 m) above the streambed on the inside of the bends and 7 ft (2.1 m) on the outside of the bends.

At section *F–F′* (fig. 28), the mudflow inundated a preflood boulder bar, which is as much as 7 ft (2.1 m) above the channel floor. Freshly battered logs of ponderosa pine and one weathered ponderosa pine log stranded from a previous flood were left on the summit of the bar; the logs indicate the flood of 1966 and the previous flood were of the same order of magnitude. Although the mudflow inundated the summit of the



NATCHI CANYON

FIGURE 28.—Sections along the Natchi Canyon–Lava Creek drainage.

bar, a depression, which is part of a side drainage that is from 3 to 4 ft (0.9 to 1.2 m) lower than the bar and between the bar and the left bank, was not inundated by water or mud during the flood of 1966.

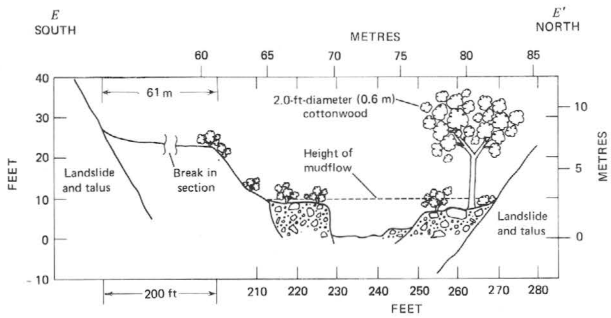
CLEAR CREEK BASIN

Clear Creek basin shows severe erosional effects from the flood of December 1966. The floodflow from Walhalla Plateau funneled through a gorge and caused considerable scouring and lateral cutting. In places Clear Creek flows between alluvial terraces as much as 30 ft (9 m) high; lower terraces support dense stands of cottonwood and other riparian vegetation. In other places the creek is enclosed by a narrow bedrock gorge.

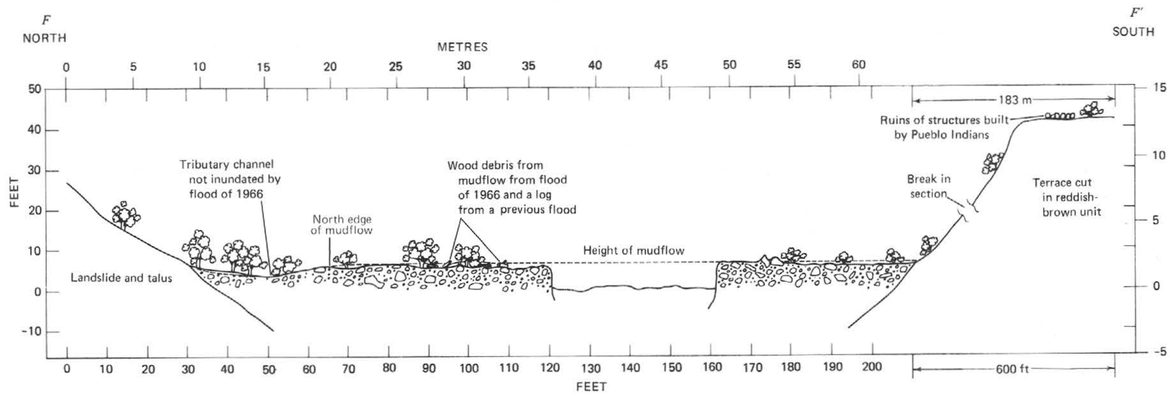
Clear Creek was inspected only at its mouth and in the area of archeological sites near Ottoman Amphitheater. Channel modifications caused by the flood included the clearing of brush, stripping of the lower limbs of trees, and lateral cutting into terraces. The lateral cutting removed part of a 6–7-ft-high (1.8–2.1-m-high) terrace and partly destroyed a prehistoric Pueblo Indian mescal pit (fig. 14), which, according to Euler, was complete and well preserved before the flood (*see* section entitled "Relation of Prehistoric and Historic Occupation to Flooding"). The lateral cutting indicates only that the flood of 1966 was one of the largest along this drainage in several centuries. Only a small amount of debris was transported to the Colorado River by Clear Creek. A few months after the flood, no evidence of deposits similar to those at the mouths of other streams was present at the mouth of Clear Creek; the Colorado flows at high velocity through a narrow rock gorge past Clear Creek.

BRIGHT ANGEL CREEK BASIN

In the upper part of Bright Angel Canyon, which was in one of the areas of concentrated precipitation during the storm of December 1966, several debris slides occurred in the amphitheaters near Uncle Jim Point (pl. 1). The slides furnished coarse and fine debris to the creek and possibly formed a mudflow that extended downstream slightly beyond the mouth of Roaring Springs Canyon. Evidence in support of a mudflow in the upper part of Bright Angel Canyon includes (1) a large boulder perched on top of a remnant of the rock dam at the confluence of Roaring Springs and Bright



Lava Creek, 0.2 mi (0.3 km) downstream from mouth of Natchi Canyon



Lava Creek, 0.1 mi (0.2 km) upstream from confluence of Lava and Chuar Creeks

NATCHI CANYON

FIGURE 28.—Continued.

Angel Canyons (pl. 1) and (2) extensive flood damage to channels restricted mainly to the small tributary draining the amphitheater north of Uncle Jim Point and to Bright Angel Creek downstream from this tributary (G. L. Beck, oral commun., 1967). The mudflow probably was extremely fluid and did not extend beyond the mouth of Roaring Springs Canyon, because there it was diluted by additional water from Roaring Springs. Between Phantom Ranch and the Colorado River, considerable mud accumulated on rocks and the sides of channels in backwater areas. Visual estimation of the amount of mud deposited indicates that Bright Angel Creek carried more sediment than Nankoweap or Kwagunt Creeks and less than Lava-Chuar Creek.

The long duration of high flow during the 1966 flood caused severe modification of the channel and flood plain of Bright Angel Creek. Before the flood in the Cottonwood Camp–Ribbon Falls area and downstream from Phantom Ranch, Bright Angel Creek flowed in a narrow channel that was generally 15–25 ft (4.6–7.6 m) wide and less than 4 ft (1.2 m) deep (fig. 30). The flood plain that adjoined the channel was as much as 200 ft (60 m) wide and was bounded by terraces between 4 and 8 ft (1.2 and 2.4 m) above the streambed. The stream channel was bordered by thick brushy and reedy riparian vegetation. The flood plain consisted chiefly of gravel bars of different heights mantled in places by considerable vegetation (fig. 12*A*). The flood of 1966 removed the riparian vegetation, rearranged or

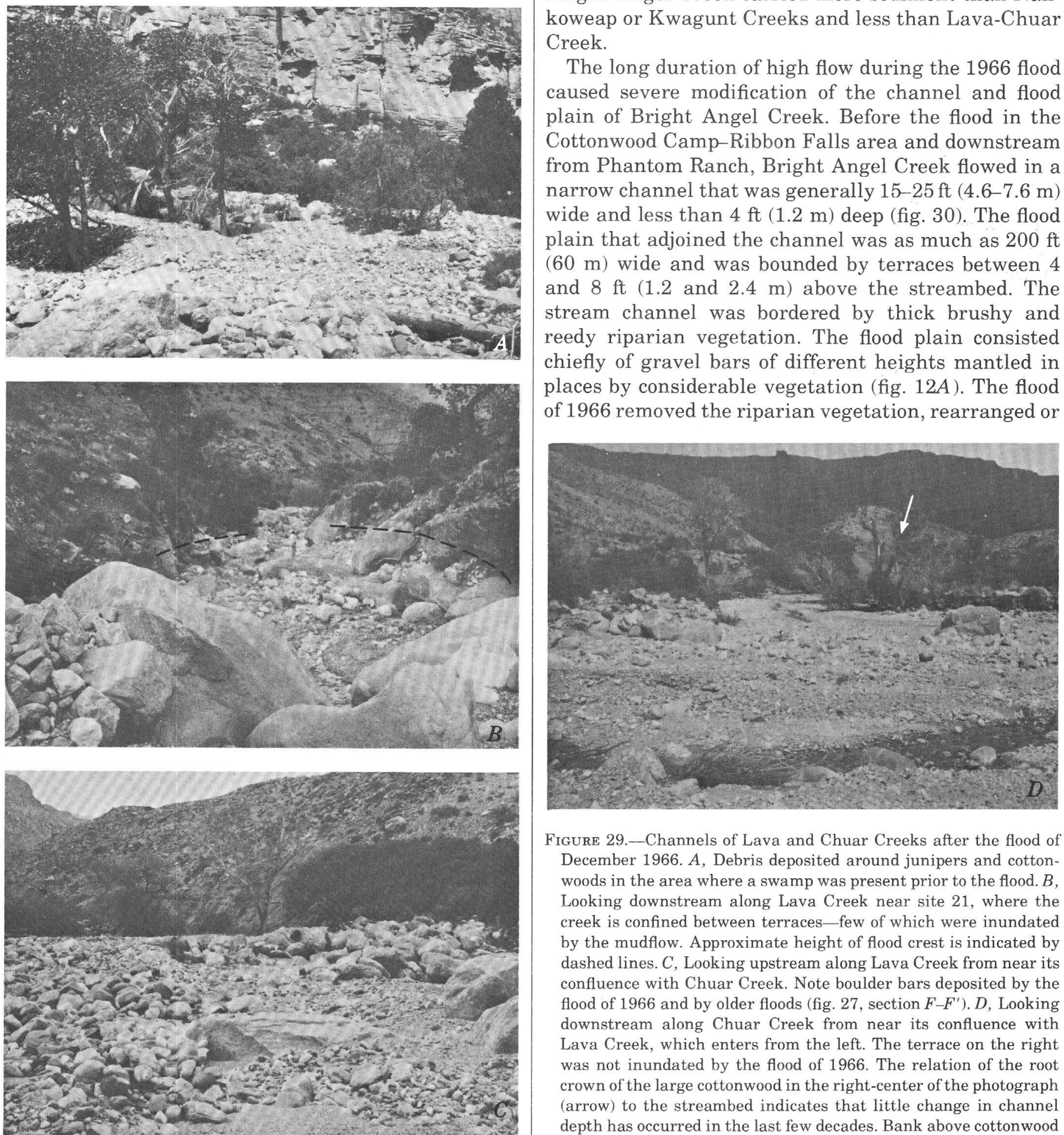


FIGURE 29.—Channels of Lava and Chuar Creeks after the flood of December 1966. *A*, Debris deposited around junipers and cottonwoods in the area where a swamp was present prior to the flood. *B*, Looking downstream along Lava Creek near site 21, where the creek is confined between terraces—few of which were inundated by the mudflow. Approximate height of flood crest is indicated by dashed lines. *C*, Looking upstream along Lava Creek from near its confluence with Chuar Creek. Note boulder bars deposited by the flood of 1966 and by older floods (fig. 27, section *F–F'*). *D*, Looking downstream along Chuar Creek from near its confluence with Lava Creek, which enters from the left. The terrace on the right was not inundated by the flood of 1966. The relation of the root crown of the large cottonwood in the right-center of the photograph (arrow) to the streambed indicates that little change in channel depth has occurred in the last few decades. Bank above cottonwood was eroded by the 1966 flood.

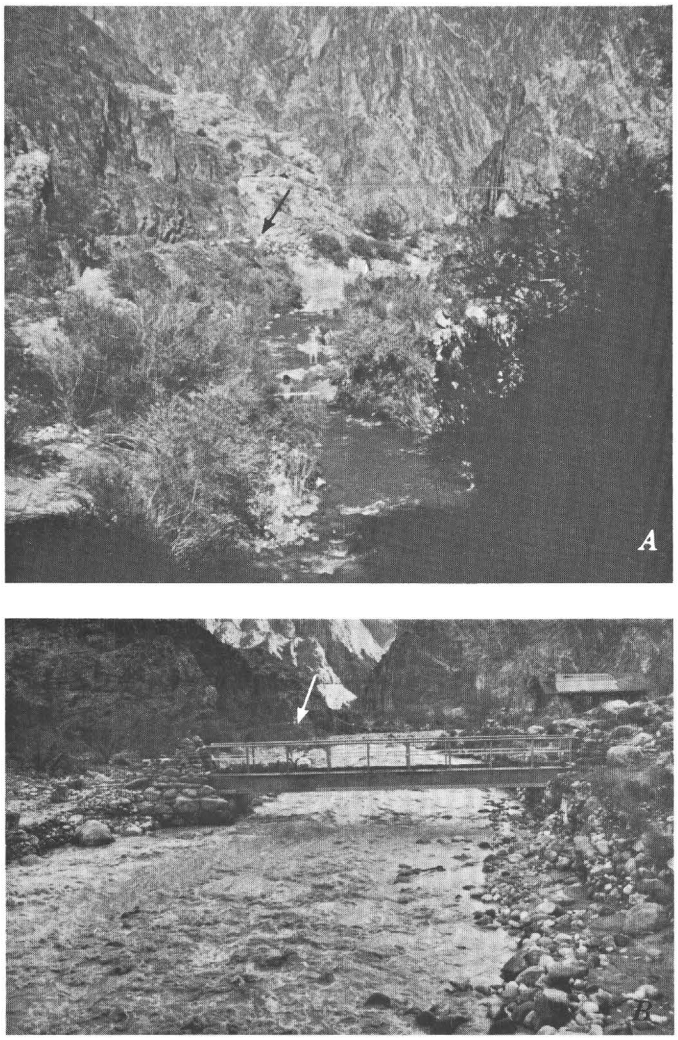


FIGURE 30.—Bright Angel Creek 1,000 ft (305 m) above mouth. *A*, Channel in August 1963. No channel changes occurred between 1963 and 1966. *B*, Channel after flood of December 1966. The arrows in photographs *A* and *B* may be used to establish a common reference at the Kaibab Trail.

scoured the bars, obliterated the channel, and removed part of the 4–8-ft-high (1.2–2.4-m-high) terrace (fig. 12*B*).

The ranch buildings at Phantom Ranch are on a low terrace on the left bank of Bright Angel Creek and are 6–8 ft (1.8–2.4 m) above the present (1967) streambed. The buildings are along the inside of a broad bend that tends to keep the flow of the creek along its right bank. Along the downstream part of the terrace, the floodflow was diverted by gravel bars formed during the flood and by bedrock protrusions that affect only high flow, causing the stream to cut a flood channel (fig. 13) from the right bank to the left bank. Between Phantom Ranch and the Colorado River, lateral cutting into the 4–8-ft-high (1.2–2.4-m-high) terrace gouged crescent-shaped scours that, in places, were more than 30 ft (9

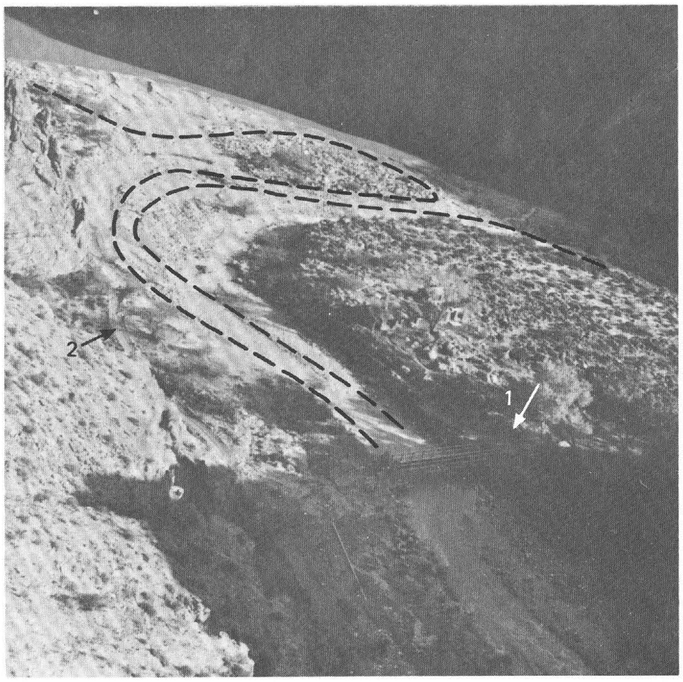


FIGURE 31.—Mouth of Bright Angel Creek after the flood of December 1966. The only remaining undamaged bridge over Bright Angel Creek is in lower right (arrow 1). Trail at left center (arrow 2) connects Colorado River suspension bridge with Phantom Ranch, which is behind the viewer. Channel boundaries before the flood were approximately as outlined by the dashed lines.

m) wide. Much of the Phantom Ranch Campground was eroded (fig. 14).

The alluvial fan at the mouth of Bright Angel Creek is several hundred feet wide. The flood deposited pebbly to bouldery sediment on the fan and as far as 1,000 ft (305 m) upstream from the mouth. At the foot bridge near the gaging station, the channel was filled to a depth of 4–6 ft or 1.2–1.8 m (R. J. Starkey, oral commun., 1967).

The boulder riffle formed by the front edge of the fan in Bright Angel Creek is the control for the gaging station on the Colorado River. Prior to the flood of December 1966, the head of the riffle was opposite the upstream side of the fan. Bouldery debris deposited by Bright Angel Creek during the flood caused the head of the riffle to move downstream several hundred feet to a point opposite the downstream side of the fan (fig. 31). Personnel familiar with this gaging station have estimated a drop of 6–9 ft (1.8–2.7 m) in channel elevation from the head of the riffle to the mouth of Bright Angel Creek; a 1924 profile of the Colorado River indicates a drop of about 6 ft (1.8 m). The stage-discharge relation at the station had remained almost constant since the station was installed in 1922. In the Colorado River the stage required for a given discharge after the flood was 4 ft (1.2 m) higher than that required for the corre-

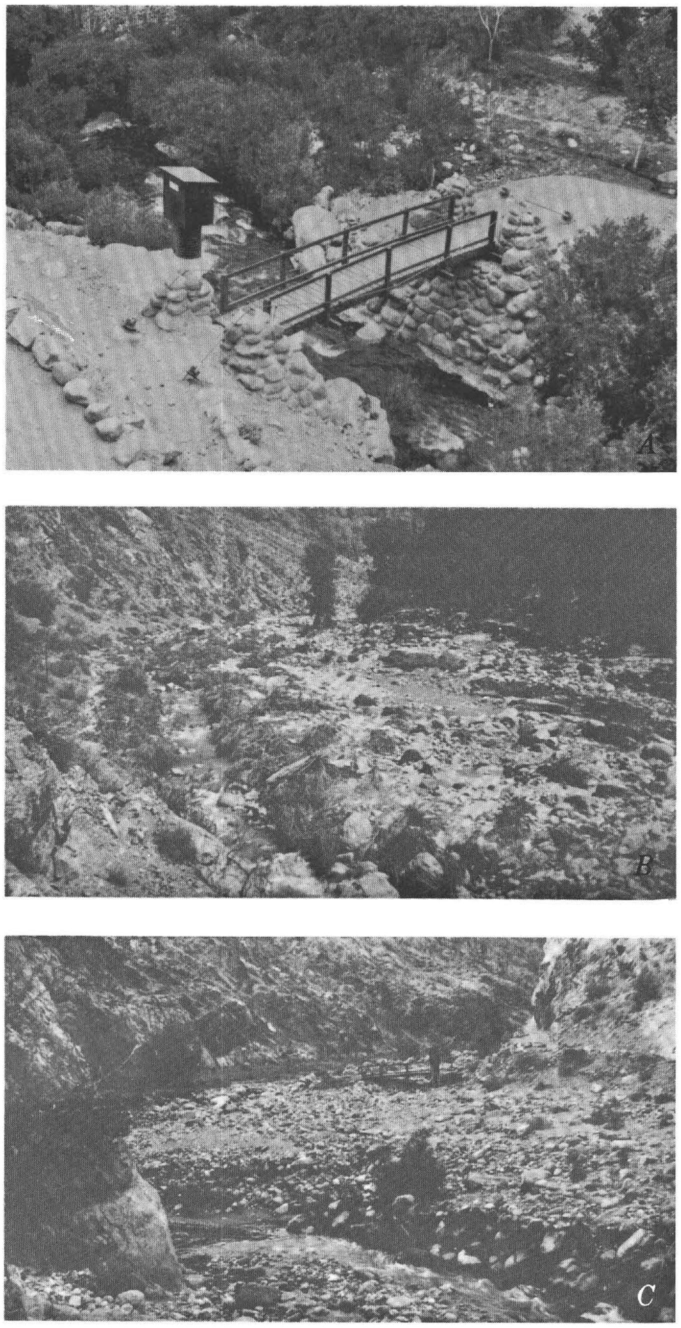


FIGURE 32.—Bright Angel Creek near Phantom Ranch before and after the flood of August 1936 (see figs. 12, 13, 14). *A*, Channel of Bright Angel Creek in May 1936. The trail to Phantom Ranch is bounded by line of rocks in left foreground. *B*, Looking upstream after the flood. Trees in center background are the ones shown near the center of fig. 13. *C*, The preflood channel is indicated by the bridge and gaging station. Looking upstream from a site near the footbridge shown in figure 31.

sponding discharge before the flood, which indicates that the new deposit of gravel and boulders at the mouth of Bright Angel Creek accumulated to a depth of at least 10 ft (3.0 m).

Although the peak discharge of the flood of August 19, 1936, in Bright Angel Creek was higher, the damage and channel modification caused by the flood of 1936 along most of the channel was much less than that caused by the flood of 1966 owing to the relatively short period of high flow. The flood of 1936 removed part of the vegetation on the flood plain and caused only minor lateral cutting into the 4–8-ft-high (1.2–2.4-m-high) terrace (fig. 32). The channel was severely modified in 1936 but was not destroyed as it was during 1966. Near the mouth of the creek and upstream from the present gaging station, the flood of 1936 deposited a large gravel bar, which caused a diversion of the channel from the left to the right bank (fig. 32*C*); the channel remained in this position through the flood of 1966.

CRYSTAL CREEK BASIN

When viewed from the air, the reach of Crystal Creek basin that was inundated and modified by the flood of December 1966 is marked by mud and debris which extends as a continuous buff band along Milk and Dragon Creeks downstream to the confluence of Crystal Creek with the Colorado River. The band of mud, which shows the maximum extent of the flood, is particularly conspicuous on the dark schist in the gorge of Crystal Creek below Dragon Creek. In contrast, only a moderate amount of flow and minor erosion occurred along Crystal Creek upstream from its junction with Dragon Creek (fig. 8; table 2).

The flood of December 1966 in Crystal Creek is considered to have consisted of three main stages: (1) the streamflow before the mudflow, (2) the mudflow, and (3) the streamflow after the mudflow. As indicated by the mudline, the mudflow formed the crest of the flood. Downstream from the confluence of Milk and Dragon Creeks, the evidence can be interpreted to indicate that the mudflow may have consisted of either a single pulse or multiple pulses.

The muddy debris was plastered in layers as much as 3 in. (about 80 mm) thick on the sides of the channel (fig. 22) and on large boulders and trees throughout the banded reach. Parts of the channel sides were smoothed, the edges of the terraces were rounded by the mudflow, and the channels of the tributaries were left several feet above the bed of the main stream (fig. 33). The muddy detritus is pale reddish brown to light brown and consists of a heterogeneous mixture of silt, very fine to fine sand and sandstone, chert, and limestone fragments less than 1 in. (about 25 mm) wide. The sand is principally subrounded to subangular clear and stained quartz similar to that in the Supai Formation and Coconino Sandstone.

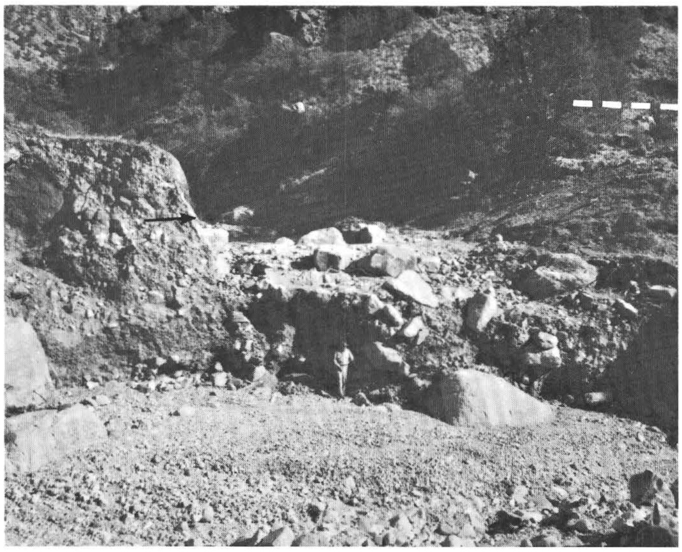


FIGURE 33.—Mudflow in Dragon Creek at the mouth of Dragon Creek tributary 2 in the upper Hindu Amphitheater. The mud flowed from left to right over the terrace at the right side of the photograph and smoothed and rounded the edge of the terrace back as much as 3 ft (0.9 m). Although the crest of the mudflow (dashed line) was 28 ft (8.6 m) above the bed of Dragon Creek, the mudflow did not move laterally into tributary 2. The bed of tributary 2 (arrow) was left "hanging" 12 ft (3.7 m) above the postflood bed of Dragon Creek where the man is standing.

The net change in the channels of Milk, Dragon, and Crystal Creeks, which were traversed by the mudflow, is one of deepening, except where aggradation took place in the short reaches upstream about 0.25 mi (0.4 km) from inner gorge 1, at location R in inner gorge 2, and at the mouth of Crystal Creek (pl. 1). Although the amount of downcutting is difficult to determine in most places, 12 ft (3.7 m) occurred at the mouth of Dragon Creek tributary 2 (fig. 33). In many places the downcutting probably was more than 5 ft (1.5 m) but in general probably was not more than 10 ft (3.0 m). Narrow 10-15-ft-deep (3.0-4.6-m-deep) trenches were cut downstream from two knickpoints on Dragon Creek. Part of the trenching may have taken place before 1966. The lowest mudmarks are within 5 ft (1.5 m) above the streambed near site 46, near the mouth of Dragon Creek tributary 2, and in the Hindu Amphitheater. Therefore, it appears that most of the channel deepening was caused by the floodflow that preceded the mudflow and (or) by the mudflow rather than by the streamflow that occurred after the mudflow.

The amount of lateral cutting that took place during the flood of December 1966 seems to have been slight—generally less than 10 ft (3.0 m)—and places where lateral cutting exceeded 25 ft (7.6 m) are uncommon. The muddy debris was deposited on the channel sides and formed a general protective mantle against erosion by postmudflow streamflow; fresh scars that would indicate postmudflow cutting, caving, or slumping of the banks were observed only in a few places.

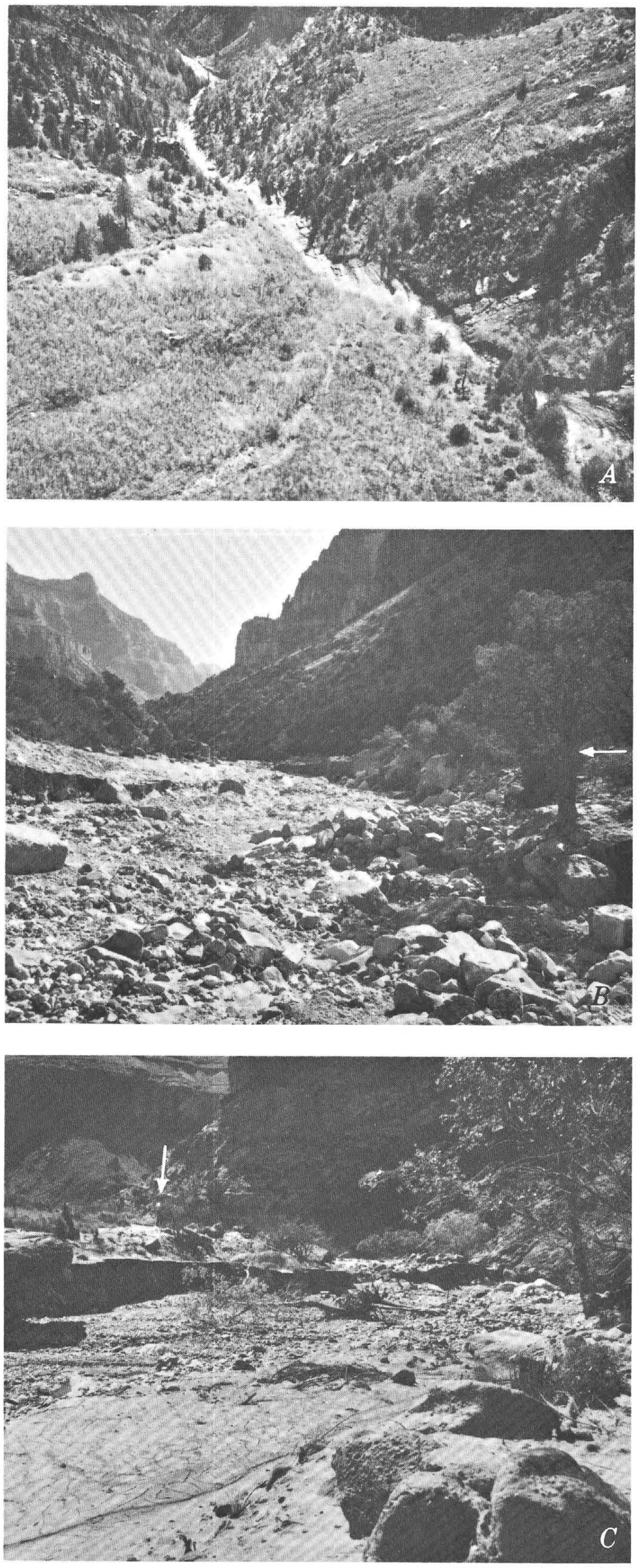
UPSTREAM FROM HINDU AMPHITHEATER

In the Milk Creek drainage area 12 fresh scars from debris slides or avalanches were noted during a helicopter reconnaissance flight (pl. 1). The amount of debris that composed a single slide was not sufficient to form the mudflow that moved downstream along Milk, Dragon, and Crystal Creeks. Therefore, the mudflow probably was formed by the coalescing of several debris slides and the picking up of considerable material in the stream channel en route.

Along Milk Creek upstream from its junction with Dragon Creek, the flood radically changed the characteristics of the channel—more than in any other reach in the Crystal Creek basin—and the mudflow cleared the channel and canyon floor of loose rock and vegetation (fig. 34*A*; fig. 35, section *A–A'*) by as much as 25 ft (7.6 m) above the present streambed. It is difficult to delineate the multiple-fill terraces in the reach because their edges were rounded and in places were covered by a layer of muddy detritus. Scours that are a few feet deep and large boulders stranded from the mudflow are common on the channel bottom. In contrast with Milk Creek, the channel of Dragon Creek above its confluence with Milk Creek was not modified by a mudflow and shows only the effects of flowing water (fig. 35, section *A–A'*).

At the mouth of Milk Creek, the channel of Dragon Creek is fairly smooth and does not contain large scours. However, about 0.10 mi (0.16 km) downstream, the channel is interrupted by a 10-15-ft-high (3.0-4.6-m-high) knickpoint, which probably formed violent rapids during the flood. The knickpoint consists of uncemented coarse alluvium that includes boulders more than 10 ft (3 m) long. The boulders are wedged so tightly that they restrict rapid downcutting. Mudmarks are preserved in the lower end of the trench, but none were found in the upper end of the trench adjoining the knickpoint, although the top of the mudflow was 7–12 ft (2.1–3.7 m) higher than the lip of the trench. It appears, therefore, that the upper end of the trench was excavated and that the knickpoint advanced several tens of feet during the streamflow that followed the mudflow.

Downstream from the knickpoint at section *B–B'* (fig. 35), the gradient flattens slightly, the channel widens (fig. 34*B*), and mud is plastered on the channel sides between 6 and 12 ft (1.8-3.7 m) above the streambed. Large boulder bars having as much as 5 ft (1.5 m) of relief suggest that some deposition took place during the flood. Perhaps part of the material removed from the



channel, as the knickpoint was advancing upstream, was deposited in this reach. The lowest terrace, which is 11 ft (3.4 m) above the present channel and was barely inundated, is capped by a thin soil (fig. 35, section *B–B'*).

Between sections *B–B'* and *C–C'*, the channel of Dragon Creek widens progressively, the amount of gravel deposited by the flood decreases downstream, and the height of the mudline decreases from 12 ft (3.7 m) to 6½ ft (2.0 m) above the streambed. At section *C–C'* (fig. 35), a 1,000-ft-long (304.8-m-long) reach of Dragon Creek was aggraded during the flood, and gravel was deposited in broad irregular bars as much as 6 ft (1.8 m) high. A remnant of a 6-ft-high (1.8-m-high) terrace, which was somewhat protected along the inside of a bend and was barely flooded, is mantled by a soil that supports upright reeds and brush. Mudmarks across the streambed on the outside of the bend, where the velocity of the current was at a maximum, were at least 10 ft (3 m) above the channel; however, splashing made the exact placement of the mudline difficult.

Below section *C–C'* in the 0.30 mi (0.5 km) reach upstream from inner gorge 1, the channel of Dragon Creek is entrenched between 20-30-ft-high (6-9-m-high) terraces composed of material that includes boulders as much as 10 ft (3 m) in diameter. The channel depth is accentuated by a sharply defined knickpoint, which probably was present before the flood but was deepened and extended by the flood into the lower part of the aggraded reach centered at section *C-C'*. The trench formed at the knickpoint has nearly vertical walls, is 15-20 ft (4.6-6.1 m) deep, and contains large scours. The intensive scouring and differences in the height of the mudmarks, which in one place are 17 and 33 ft (5.2 and 10.1 m) above the bed of the creek on opposite sides of the channel, indicate that turbulent and shooting flow occurred across and near the knickpoint.

Between inner gorges 1 and 2, the channel of Dragon

FIGURE 34.—Effects of the flood and mudflow of December 1966 in Milk and Dragon Creeks. *A*, Cleared and smoothed channel of Milk Creek after the mudflow. Note that the mudflow cleared the channel of gravel, loose boulders, and vegetation. *B*, Channel of Dragon Creek looking downstream from section *B–B'* (fig. 35). Terraces along both banks were damaged but not destroyed. The lower 4 ft (1.2 m) of the juniper in the right foreground is plastered with mud. Crest of mudflow is indicated by arrow. *C*, Channel of Dragon Creek looking downstream in the main part of the Hindu Amphitheater toward the mescal pit (Ariz. B:16:42), where the men are standing (arrow). Muddy debris deposited by the mudflow in left foreground extends downward to within 3 ft (0.9 m) of the present streambed. Cutting by the mudflow and streamflow stages of the flood formed a benchlike feature on the left bank 6-7 ft (1.8-2.1 m) above the streambed.

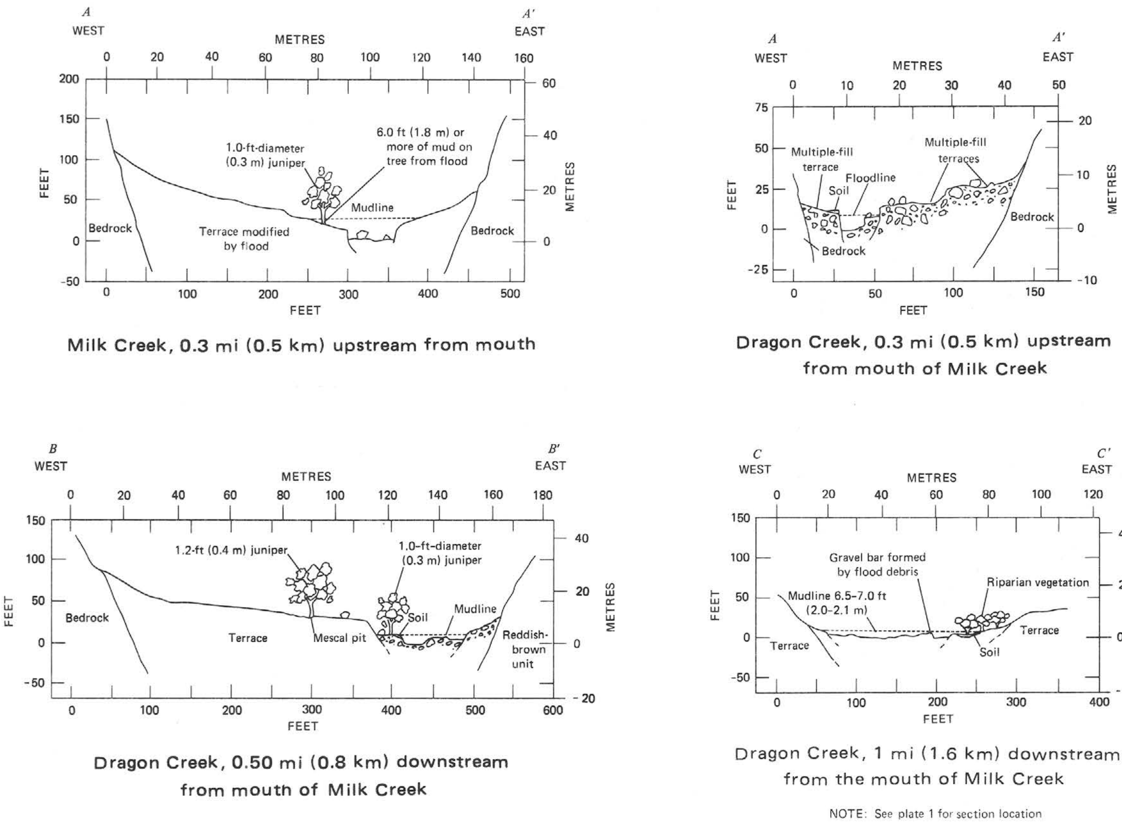


FIGURE 35.—Sections along Dragon and Milk Creeks.

Creek is 50-70 ft (15-21 m) wide and adjoins prominent vertical-faced terraces that generally are between 15 and 35 ft (4.6 and 10.7 m) high (fig. 7). Limestone is exposed in the streambed for a few tens of feet at inner gorge 1 and for about 0.75 mi (1.2 km) between inner gorge 2 and tributary 2. The mudline between inner gorges 1 and 2 is as much as 44 ft (13.4 m) high, which is the highest mark measured along the entire drainage. The high mudline resulted from shooting flow that swung around a bend. The mudline lowered progressively as the channel straightened downstream from the bend; in a distance of 150 ft (46 m), the height of the mudline decreased to 21 ft (6.4 m). At the mouth of tributary 2, the mudline on the right bank of Dragon Creek is as low as 16 ft (4.9 m) above the streambed, whereas, the mudline on the left bank is 28 ft (8.5 m) above the streambed. In places the mudflow covered parts of the enclosing terraces; for the most part, however, the mudlines are 1 or 2 ft (0.3 or 0.6 m) below the tops of the terraces. Near site 46 (figs. 7, 17), the flood inundated most of the terrace that was 14-16 ft (4.3-4.9 m) above the streambed and destroyed or modified beyond recognition the mescal pit (Ariz. B:16:41) that had been located the previous summer; the mudflow covered the entire canyon bottom. (See the sections entitled "Magnitude of Floods, Crystal Creek Basin" and "Relation of Prehistoric and Historic Occupation to Flooding.")

The bed of tributary 2 at its mouth was 12 ft (3.7 m) above the bed of Dragon Creek when the site was visited in February 1967; the tributary now must flow over a newly cut vertical dropoff before it enters the channel of Dragon Creek (fig. 33). The material from which the dropoff is cut is continuous with the material that forms the adjacent alluvial terraces and not with the material deposited by the flood. If the hanging bed of tributary 2 represents the pre-1966 flood level of the bed of Dragon Creek, then the bed of the creek was lowered 12 ft (3.7 m) during the flood. The waterline that defines an area of ponding at the mouth of tributary 2 is additional evidence that trenching took place during the flood; the waterline is 8 ft (2.4 m) above the bed of the tributary. It seems unlikely that the mudflow in Dragon Creek dammed the tributary and caused the ponding because the rate of flow of tributary 2 was estimated to be insufficient to fill a pond 8 ft (2.4 m) deep and 40 ft (12 m) wide during the extremely short time that it probably took the mudflow to pass the mouth of the tributary (table 2). Therefore, the waterline probably represents the maximum level of Dragon Creek before the mudflow and before much erosion of the dropoff at the mouth of tributary 2 had taken place.

HINDU AMPHITHEATER

Dragon Creek flows in an alluvial-floored channel through nearly all of inner gorge 2 in the northeastern part of the Hindu Amphitheater. Bedrock is exposed in the bed of the creek at the head of the gorge, where the gorge is less than 20 ft (6 m) wide in places. At a spring in inner gorge 2, the mudline is 15½ ft (4.7 m) above the present streambed. The flood covered and mildly scoured a terrace 7 ft (2.1 m) above the bed of the creek; a 3-ft-diameter (0.9-m-diameter) cottonwood growing on the terrace was left standing upright.

The height of the mudline above the channel gradually decreases downstream, and, at location R (pl. 1), mudmarks are not present on the walls of the gorge. An alluvial terrace at this location is only 6½ ft (2.0 m) above the streambed (pl. 1). The terrace is capped by a grayish-brown soil less than 1 ft (0.3 m) thick that contains substantial organic material. Reeds and other swampy type plants growing on the terrace indicate that they were situated at or near the level of the streambed prior to the flood. The plants remained upright; neither they nor the top of the terrace were inundated by mud or water. An equally high gravel bar that occupies most of the channel was deposited by the flood along the terrace. A hypothesis as to what may have caused the mudflow and streamflow to pass this point without inundating the 6½-ft-high (2.0-m-high) terrace is that (1) the channel was deepened by premudflow streamflow, (2) the mudflow passed by in the newly deepened channel, and (3) the channel was aggraded to its present (1967) level, including the burying of marks left by the mudflow, by postmudflow streamflow.

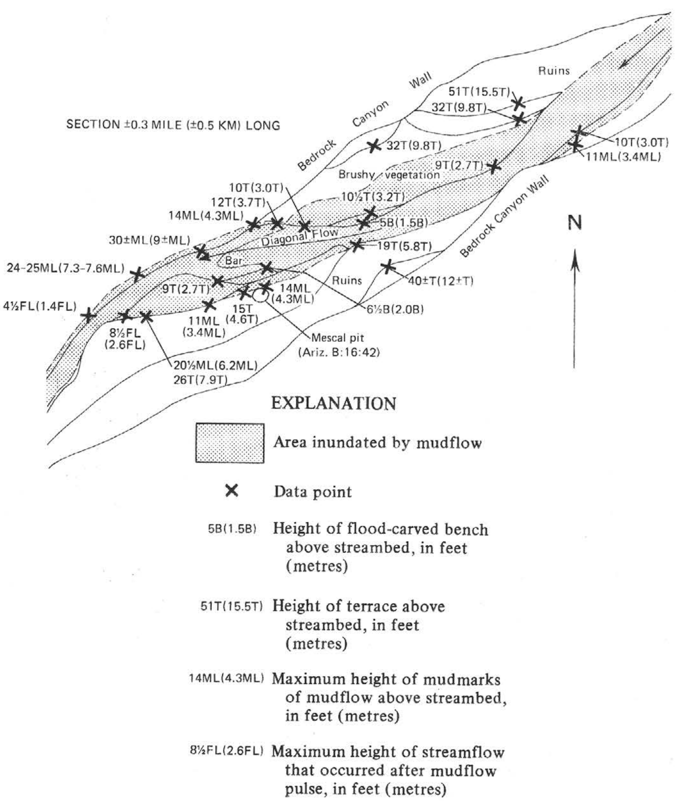


FIGURE 36.—Main part of Hindu Amphitheater showing distribution of mudflow and alluvial terraces along Dragon Creek.

Downstream from location R, the mudmarks gradually increase in height to 11 ft (3.4 m) above the streambed. Conspicuous mudmarks were seen on the walls of the gorge between location R (pl. 1) and the main part of the Hindu Amphitheater. In this reach, remnants of old barlike features mantled by small cottonwoods and other vegetation remain slightly above the mudline. Gravel was deposited at places in the channel and overlapped onto the heads of the barlike features.

In the main part of the Hindu Amphitheater multiple-fill terraces are the best developed of any in the Crystal Creek basin (fig. 36). A prehistoric mescal pit (Ariz. B:16:42) along the edge of the mudflow is on a 15-ft-high (4.6-m-high) terrace (figs. 17, 35*C*, 37). (See section entitled "Relation of Prehistoric and Historic Occupation to Flooding.") The terrace is protected from stream erosion by part of a 19-ft-high (5.8-m-high) terrace that generally diverts high flows diagonally to the opposite side of the channel (fig. 36). The height of the mudline increases progressively from about 10 ft

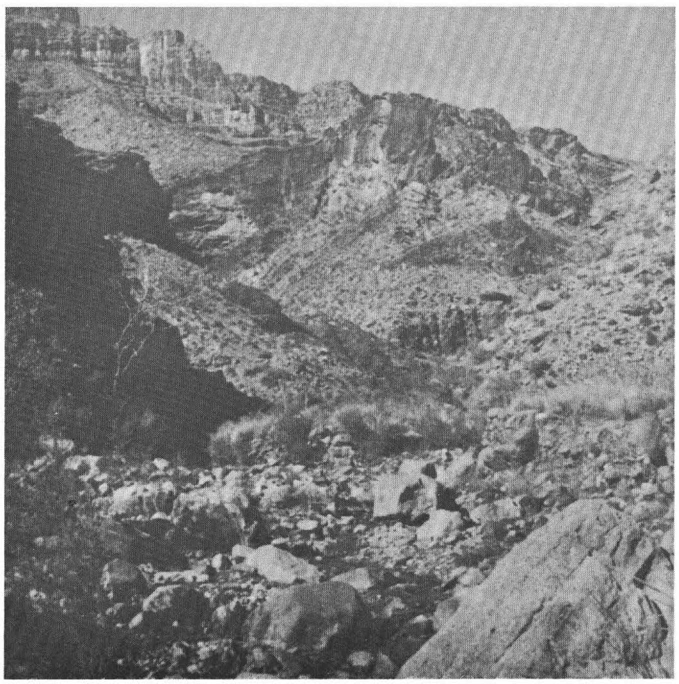


FIGURE 37.—Crystal Creek in May 1966. Looking upstream along Crystal Creek about 0.5 mi (0.8 km) downstream from its confluence with Dragon Creek.

(3.0 m) upstream from the mescal pit to 20½ ft (6.2 m) in a narrow channel at the downstream end of the reach (figs. 16*A*, 36).

DOWNSTREAM FROM HINDU AMPHITHEATER

Dragon Creek enters a narrow canyon downstream from the main part of the Hindu Amphitheater near its confluence with Crystal Creek. The mudflow and floodwater swept the canyon clear of previously deposited debris (fig. 37) and transported it to the mouth of Crystal Creek, where part was added to a boulder fan that extended into the Colorado River prior to the flood (fig. 38). The detritus deposited by the mudflow of 1966 includes boulders as much as 8 ft (2.4 m) in diameter and is the coarsest deposit at the mouth of Crystal Creek. People familiar with the area—R. C. Euler; Wayne Learn, a helicopter pilot; and rivermen (oral commun., 1967)—report that the boulder fan is much larger and extends closer to the opposite bank of the Colorado River than it did before the flood of 1966 and that Crystal Rapids are much rougher and probably higher than they were before the flood. The Colorado River survey topographic map (sheet C) printed in 1924 and the topographic map of the Bright Angel quadrangle completed in 1962 also indicate that the fan of Crystal Creek extends about 200 ft (60 m) farther into the channel of the Colorado River than it did before the flood, narrowing the channel of the river to about 100 ft (30 m). (See pl. 1.)

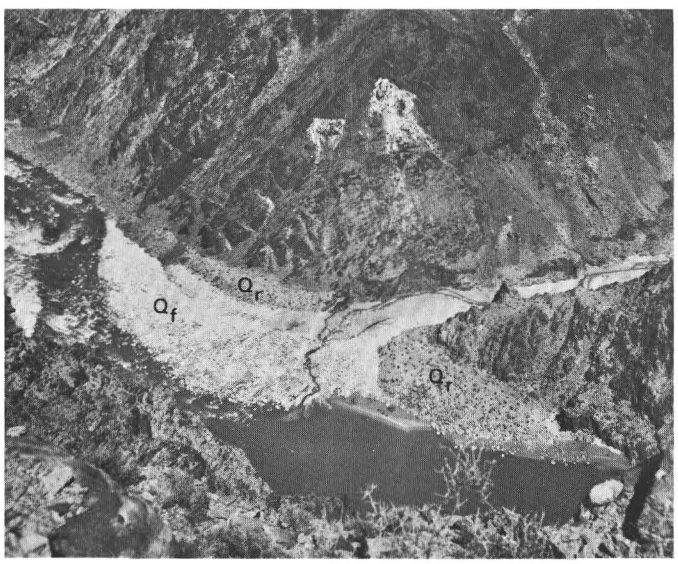


FIGURE 38.—Fan at mouth of Crystal Creek in April 1967. Flow of the Colorado River is from right to left. Light-colored materials were deposited during the flood of December 1966; the fan deposits (Qf) are composed of gravel, including large boulders. Note terrace and dissected alluvial fan (Qr) above the Colorado River.

SHINUMO CREEK BASIN

As a result of the flood of December 1966, at least seven large mudflows occurred in the northeastern part of the Shinumo Creek drainage basin (pl. 1). The mudflows and several debris slides originated principally from the Hermit Shale at the head of Merlin Abyss, along the main stem of Shinumo Creek, and in Modred Abyss. From aerial reconnaissance, all the mudflows appeared to have been rather fluid except for the one in Kanab Canyon. At least four mudflows moved downstream 1 mi (1.6 km) or more along the canyon floor after debouching from the steep canyon sides. Two of the mudflows in Modred Abyss traveled more than 1.5 mi (2.4 km). The mudflows cut conspicuous scars along channels on the long steeply forested slopes. Although the stream channels were swept rather clear of loose boulders, muddy debris was deposited along the upper parts of the channel sides and on the adjoining terraces.

MUDFLOW AT THE MOUTH OF KANAB CANYON

A spectacular mudflow that terminated at Modred Abyss—noted originally by Norman Browning, a helicopter pilot (oral commun., 1967)—collected as a 1,000-ft-long (300-m-long) mass at the mouth of the stream that drains Kanab Canyon (fig. 39*A*). From all appearances, this mudflow and the short mudflow in Lava Canyon upstream from its confluence with Natchi Canyon were much more viscous than the other mudflows in the north rim area. Most of the material composing the mudflow probably was picked up en route along the stream channel in Kanab Canyon. The stream channel, except where it cascades over cliffs, was smoothed out. In places the channel was scoured to bedrock and largely cleared of detritus and brush, forming a huge scar on the side of the canyon. One small slide below Galahad Point occurred after the mudflow; the base of the slide is in the channel of Kanab Creek and is almost undissected.

The mudflow deposits are an unsorted reddish-brown mixture that ranges from clay to boulders; grain sizes including and smaller than coarse sand make up the bulk of the material. Much of the coarse fraction is limestone. Most of the boulders are less than 3 ft (0.9 m) in diameter, and a few are as much as 5 ft (1.5 m) in diameter (fig. 39*B*, *C*). Trunks and large branches of conifers are present in the detritus, and a large amount of wood debris accumulated along the top of the mudflow (fig. 39*D*). When dry, the muddy debris is extremely hard; the drying was rather uniform, and few shrinkage cracks are apparent.

The mudflow material at the mouth of Kanab Canyon is as much as 15 ft (4.6 m) thick and 75–100 ft

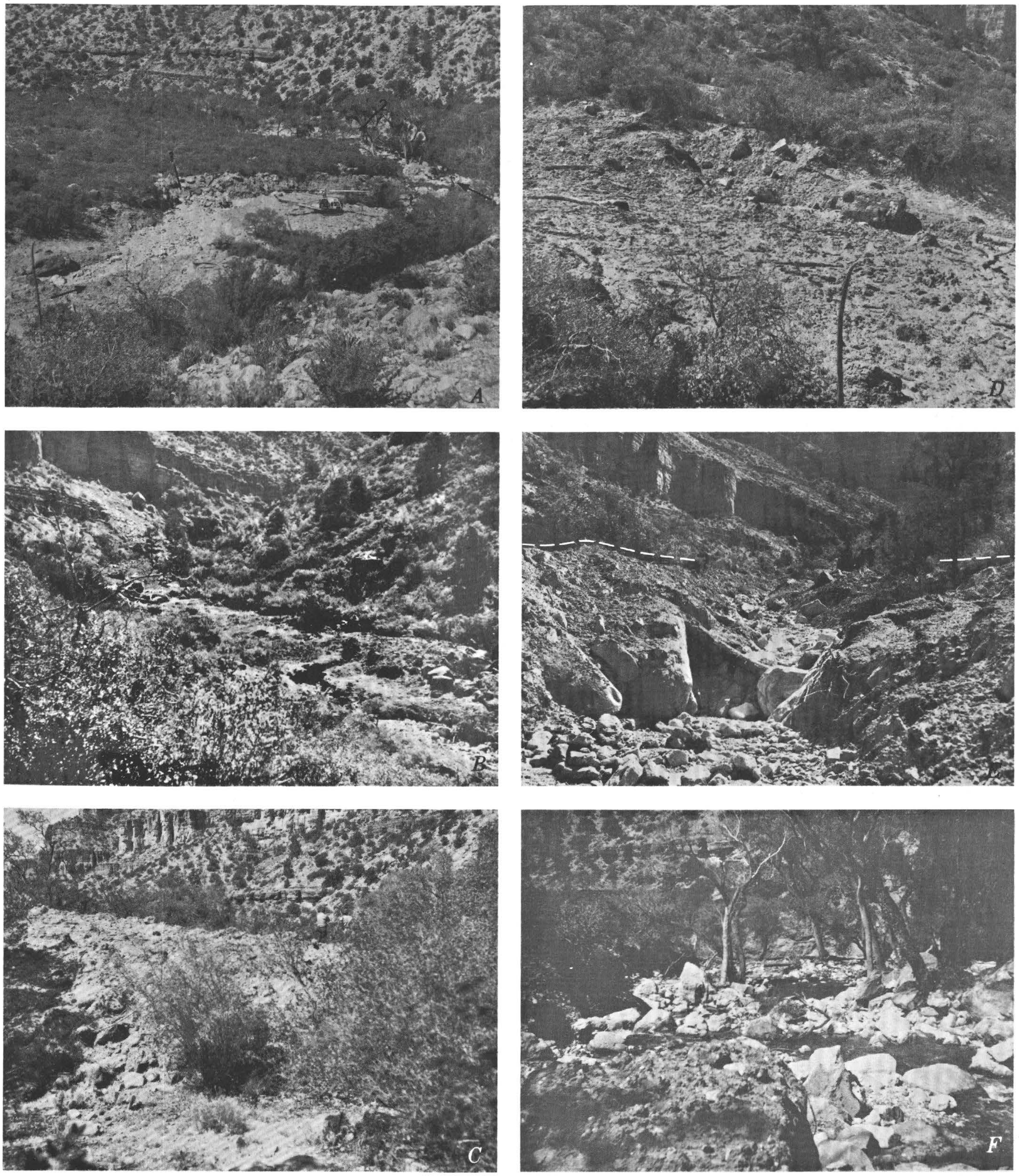


FIGURE 39.—Explanation on facing page

(23–30 m) wide. The snout of the mudflow temporarily dammed the stream channel in Modred Abyss (fig. 39*E*). Mud on boulders and tree trunks indicates that the mudflow in the stream channel was between 8 and 10 ft (2.4 and 3.0 m) thick and that the mudflow extended 15 ft (4.6 m) beyond the channel. Along the stream in Kanab Canyon, poorly formed lobes of the mudflow covered the dense brushy vegetation on the low terraces adjacent to the channel to a depth of 8 ft (2.4 m). The cross-sectional profile of the mudflow was U- to V-shaped (fig. 39*F*), forming an 8-13-ft-deep (2.4-4.0-m-deep) notch in the central part of the flow; the location of the notch probably coincided with the premudflow channel. Marks left by the streamflow that occurred after the mudflow are displayed only in the bottom 1½-2 ft (0.5-0.6 m) of the notch.

EFFECTS OF STREAMFLOW

In general, the effects of the flood of December 1966 are much less prominent along Shinumo Creek than along most other creeks. Along the Shinumo Creek tributary that drains Modred Abyss, the flood cleared the channel of brush and changed the shapes of bouldery gravel bars. Near the mouth of Kanab Canyon, large scours that now contain pools of water were excavated in the gravelly streambed (fig. 39*E*). In the wider parts of the stream channel and downstream from bends, root crowns of cottonwoods were buried by 3 ft (0.9 m) of gravel. Because of the abundance of boulders, irregular debris marks are from 3-6 ft (0.9-1.8 m) above the streambed and cover a 20-60-ft-wide (6-18-m-wide) strip of the canyon floor. Riparian vegetation protected the sides of the channel from severe erosion, but, where the streamflow was directed against the bank, lateral cutting removed as much as 5 ft (1.5 m) of sediment.

Shinumo Creek near its confluence with White Creek flows on a 200-300-ft-wide (60-90-m-wide) canyon floor. Minor cutting took place during the flood at site 54 (fig. 40, section *A–A'*) and resulted only in root exposure of some of the riparian vegetation (fig. 4). For 0.3 mi (0.5 km) downstream from its junction with White Creek, the channel of Shinumo Creek contains coarse-gravel bars. At section *B–B'* (fig. 40), a boulder

FIGURE 39.—Mudflow at the confluence of Kanab Canyon and Modred Abyss. *A*, Terminus of mudflow that moved down Kanab Creek (leader 1) and ended along the stream in Modred Abyss (leader 2). Looking downstream and across at terminus of mudflow. Arrows indicate direction of flow. Effects of the streamflow that followed the mudflow are evinced by the clean gravel in the notchlike channel. *B*, View looking upstream along the mudflow that originated in Kanab Canyon. Photograph taken just left of *A*. Photographs *A* and *B* show almost the entire mudflow deposit. *C*, Right edge of viscous mudflow that flowed downstream in Kanab Canyon. Man is standing on mudflow. Photograph taken between the helicopter and the stream in Modred Abyss. *D*, Wood debris on top of mudflow at mouth of Kanab Canyon. *E*, Mudflow debris near the mouth of Kanab Canyon. The light-colored or clear boulders were cleaned by streamflow that occurred after the mudflow event. The log in the middle foreground was carried by the mudflow. The mudflow is concave upward and forms a notch or channellike feature that was downcut only slightly by the streamflow. Note lateral extent of mudflow (dashed lines). *F*, View looking downstream along Modred Abyss at confluence with Kanab Canyon. Mudflow that originated from the left in Kanab Canyon crossed the channel but was subsequently eroded out during the flood.

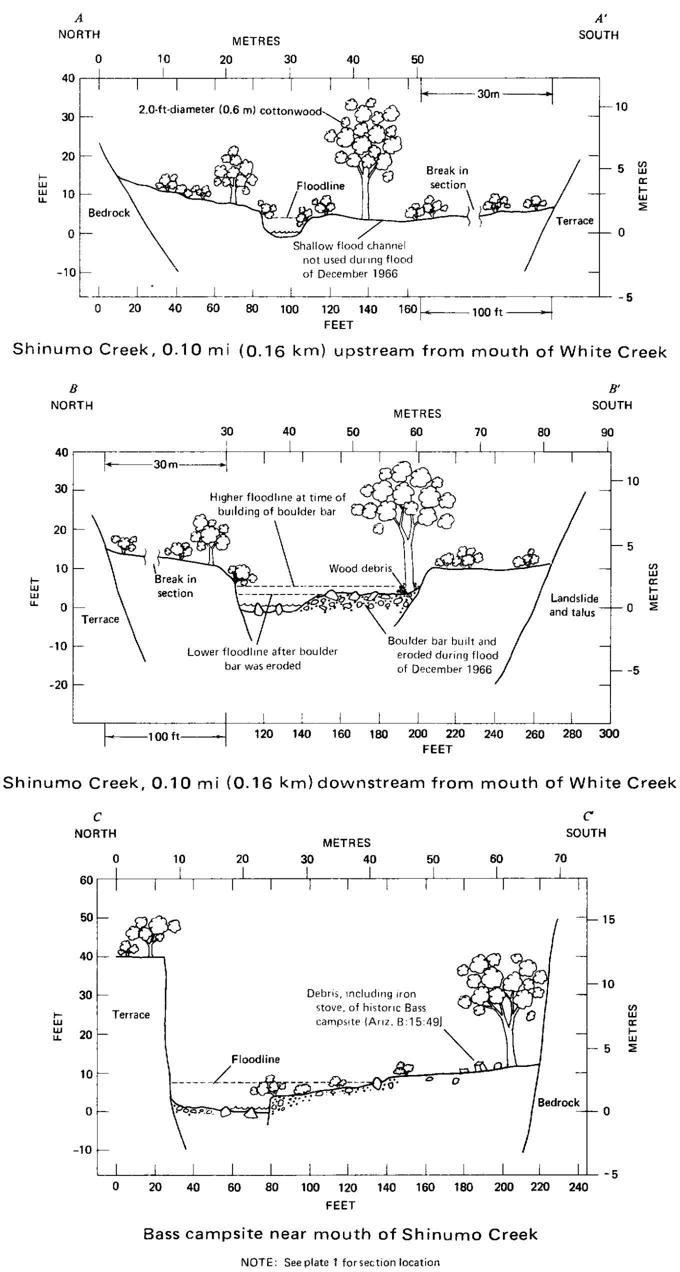


FIGURE 40.—Sections along Shinumo Creek.

bar has an average height of 4 ft (1.2 m) between terraces that are 10 and 12 ft (3.0 and 3.7 m) high. Wood and other debris left by the flood of 1966 accumulated at two levels—7 ft (2.1 m) and 3½ ft (1.1 m) above the present streambed. The higher debris level represents the crest of the flood, which was probably concurrent with the maximum buildup of the gravel bar. During the waning stage of the flood, water probably deposited debris at the lower level and trenched the present channel of the creek partly into the gravel bar. After all this aggradation and subsequent cutting, the present channel has nearly the same depth as that of the preflood channel.

Shinumo Creek flows through a narrow canyon—from 50 to 200 ft (15-60 m) wide—downstream from section *B–B′* to its mouth. In this reach the flood erosion consisted mainly of the lateral cutting of alluvial terraces. Downcutting was slight because in places Shinumo Creek flows on bedrock. Small gravel bars formed, which are not as large or extensive as the ones near section *B–B′*. At section *C–C′* (fig. 40), the floodwater encroached along the edge of the historic site (Ariz. B:15:49) that was occupied by William W. Bass about 1890–1910 (see section entitled "Relation of Prehistoric and Historic Occupation to Flooding").

TAPEATS CREEK

The flood of December 1966 was a minor event in the history of Tapeats Creek, but the creek shows effects of older floods. Wood debris from one period of high streamflow was recognized about 5 ft (1.5 m) above the level of the creek. According to R. C. Euler, a much larger flood occurred in the summer of 1961, and it is represented by mud debris and logs left on the 7–11-ft-high (2.1–3.4-m-high) terrace (fig. 41). Reconstruction of the mudline from remnants of the debris gives a height of 10-11 ft (3.0–3.4 m) above the present bed of the creek. In places the muddy debris formed lobes and lobelike masses that are composed of unsorted silty sand and some small pebbles. The composition and configuration of the debris indicate that it was deposited during a mudflow. Dead fully grown cheat grass from the previous summer was on the muddy debris when the area was visited in May 1967, which proves that this mudflow antedates the flood of 1966. The 1961(?) mudflow and accompanying streamflow apparently caused some lateral cutting that is not fully healed by vegetation. In places the mudflow moved straight along the canyon floor without regard to the sinuous channel that is incised into the 5-ft-high (1.5-m-high) terrace. The terrace was not badly eroded, although it was submerged 5-6 ft (1.5-1.8 m) by the mudflow. The terrace supports many 1–2-ft-diameter (0.3-0.6-m-diameter) cottonwoods, some of which may have been growing at the time of the mudflow.

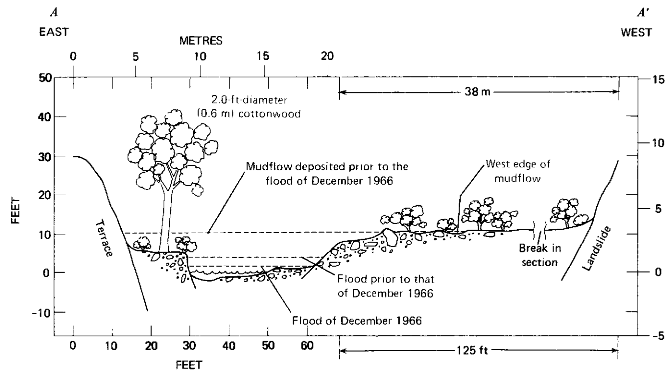


FIGURE 41.—Section along Tapeats Creek, looking downstream.

SUMMARY

The formation of mudflows, extensive channel erosion, damaged archeological sites, and high flood peaks indicate that the flood of December 1966 was a rare event in the eastern Grand Canyon area. The storm deluged part of the Kaibab Plateau with as much as 14 in. (360 mm) of rainfall. In general, the storm was concentrated on the windward southern part of the Kaibab Plateau. High flows as a result of the storm caused extensive channel damage in Nankoweap, Kwagunt, Chuar, Clear, Bright Angel, Crystal, and Shinumo Creek basins.

The most spectacular event of the storm was the formation of mudflows and debris slides—avalanches. Two of the mudflows in Crystal and Chuar Creek basins were especially fluid and extended from the sides of the Kaibab Plateau to the Colorado River, a distance of more than 7 mi (11.3 km). At least nine other mudflows moved more than 0.5 mi (0.8 km). Although these are the first mudflows to be documented in the eastern Grand Canyon area, remains of an older mudflow were recognized along Tapeats Creek. More than 80 debris slides occurred in the amphitheaters of the side tributary gorges bordering the Kaibab Plateau, and about 10 occurred on the summit of the plateau.

Record flows occurred along Bright Angel Creek, the only creek that is gaged in Grand Canyon. The peak flow of 4,000 ft^3/s (about 110 m^3/s) was slightly lower than the peak flow in 1936, but the flow volume and duration were much greater. The recurrence interval obtained from regional flood-frequency relations is about 100 years for the peak discharge.

The flood discharge along Dragon Creek, a tributary to Crystal Creek, appears to have been of greater magnitude than that in Bright Angel Creek. The flood components consisted of streamflow before the mudflow, the mudflow that composed the crest of the flood, and streamflow after the mudflow. A mescal pit that had been utilized by prehistoric Pueblo Indians about

A.D. 1100 was destroyed or covered by mud, which indicates that the flood of December 1966 was the largest flood in the last 800 years.

The flood of 1966 damaged or destroyed two prehistoric mescal pits that were constructed by the Anasazi Pueblo Indians between A.D. 1050 and 1150—the previously mentioned pit along Dragon Creek and one along Clear Creek. The crest of the mudflow barely wetted part of another mescal pit along Dragon Creek. The Indians probably were well aware of flash floods because their permanent structures were built high on terraces or along cliffs.

The flood damage to cultural features was mainly to a pipeline, the cross-canyon Kaibab Trail, buildings, and campgrounds in Bright Angel Canyon and to roads on the Kaibab Trails. Most of the road damage was caused by slides near Bright Angel Creek along the paved highway leading to Point Imperial and by washouts along dirt roads in Kanabownits Canyon and in the North and South Canyon drainages.

On the Kaibab Plateau, the flood of 1966 affected mainly the grass-covered parks and valleys, which contained few active scours or discontinuous gullies before the flood. The flood enlarged the old scours and gullies and cut many new scours in Bright Angel and Clear Creek basins. Scouring was particularly noticeable where the flow was more than 1 ft (0.3 m) deep. Renewed arroyo trenching occurred along two drainages—in the lower part of the Walhalla Glades and in Outlet Canyon. The arroyos were deepened and widened as a result of coalescing of large scours. In the tributary gorges of the eastern Grand Canyon the flood of 1966 affected mainly the channels of Nankoweap, Chuar-Lava, Clear, Bright Angel, and Crystal-Dragon Creeks.

The alluvial fans at the mouths of Bright Angel, Crystal, Nankoweap, and Kwagunt Creeks were enlarged by the flood and now extend into the channel of the Colorado River. Debris deposited by the flood at the mouth of Bright Angel Creek changed the stage-discharge relation at the Colorado River near Grand Canyon gaging station; this relation was nearly constant for 1922-66. The fan in Crystal Creek was enlarged by about 200 ft (60 m), and the flood deposited large boulders in the channel of the Colorado River, which greatly increased the roughness of Crystal Rapids.

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