The Catastrophic Late Pleistocene Bonneville Flood in the Snake River Plain, Idaho

GEOLOGICAL SURVEY PROFESSIONAL PAPER 596

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By HAROLD E. MALDE

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A study of colossal features of erosion and deposition produced along the Snake River by sudden overflow of Lake Bonneville

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By Harold E. Malde

ABSTRACT

A catastrophic flood caused by overflow and rapid lowering of Pleistocene Lake Bonneville at Red Rock Pass near Preston, Idaho, descended Marsh Creek Valley and reached the Snake River Plain at the site of Pocatello. Large tracts in the upper Snake River Plain were inundated, particularly an area near American Falls and a basin that surrounds Rupert. Farther downstream, the Snake River canyon that extends 200 miles west of Twin Falls was flooded to a depth of 300 feet. Spectacular erosion in the form of abandoned channels, spillways, cataracts, and scabland identifies the flood path between American Falls and Twin Falls, and the canyon farther west is strewn with huge boulders—some of them more than 10 feet in diameter—which are heaped in enormous bars of boulders and sand that rise nearly 300 feet above the canyon floor.

The Bonneville Flood almost certainly was caused by capture of the Bear River, which resulted in greatly augmented inflow to the Bonneville basin. The details of this event have been studied by R. C. Bright, University of Minnesota, who estimates from several radiocarbon dates—some from the Bear River drainage and others from the flood path—that spillover at Red Rock Pass first occurred about 18,000 years ago. However, I believe that the history of Bear River deduced by Bright, as explained in his Ph. D. thesis of 1963, agrees better with initial spillover at about 30,000 years ago, as indicated by a radiocarbon date for molluscan fossils associated with flood debris near American Falls and by relict soil preserved on the flood deposits.

Whatever the age of the Bonneville Flood, it undoubtedly represents discharge from a lake level above the Bonneville shoreline and is not at all related to subsequent downcutting to the present level of Red Rock Pass—the Provo shoreline. Overflow could have been across weakly consolidated surficial material in Red Rock Pass at a height of as much as 100 feet above the Bonneville shoreline. If so, the flood volume was 380 cubic miles. A probable maximum discharge of about one-third of a cubic mile per hour is computed by C. T. Jenkins, U.S. Geological Survey, at a canyon neck near Swan Falls, south of Boise, which acted as a gigantic venturi flume. The flood duration at maximum discharge could therefore have been at least 6 weeks. If peak flow lasted only a few days, as seems likely, voluminous discharge could have continued for at least a year.

Debris left by the Bonneville Flood along the Snake River canyon is known by the descriptive geologic name, Melon Gravel. It displays an array of lithologic and physiographic features that demonstrate torrential origin in rapidly moving deep water. The Melon Gravel was derived from local basaltic lava flows and is otherwise distinguished lithologically by extremely poor sorting (boulders and sand), by phenomenal sets of giant crossbeds, and by extraordinarily abrupt changes in grain size. Rounded basalt boulders just below canyon constrictions are commonly larger than 5 feet and can be identified as having come from outcrops not more than a few miles upstream. The gravel occurs mainly in wide places along the canyon as groups of bars of colossal size that together resemble the greatly magnified bed of a braided stream. In the lower reach of wide segments along the canyon, bouldery flood debris gives way to sandy deposits, presumably because of retarded flow. Bars of gravel block the mouths of some tributary valleys, but at most places the bars stand midway between the canyon walls, from which they are separated by marginal channels as deep as 150 feet. The constructional form of these bars is well preserved, and they apparently have been little modified by erosion since the flood.

Fine-grained alluvium formed broad flats in tributary valleys that were blocked by deposits of Melon Gravel. Other fine-grained material was dropped in backwater areas of temporary lakes that filled broad segments of the Snake River canyon during passage of the flood.

The marginal channels were formed as a consequence of the Melon Gravel being washed into wide places along the Snake River canyon and then being dumped in midstream. Some of these channels wind several miles along the canyon walls; they are generally perched 100 feet or more above the present Snake River. Like the adjoining gravel bars, they demonstrate that the canyon flowed deep with floodwater at peak discharge.

Distinctive scabland was formed by erosion during the Bonneville Flood, especially in the upper Snake River Plain above Twin Falls. It forms an irregular surface of scoured basalt diversified by branching channels, dry falls, and rock basins. Lack of soil distinguishes the scabland most obviously, but subtle signs of basalt erosion—such as smoothed, polished, and fluted surfaces, as well as stripping and plucking evident to a trained observer—also indicate a former forceful flow of water.

The flood path through the Snake River Plain closely followed the present Snake River and is now well known. Floodwater debouching on the plain at Pocatello entered a lake that was held by a lava dam near American Falls, and bouldery debris 50–80 feet thick was dumped on the lake bottom. Water escaped over and around the lava dam by several routes and then descended in a broad swath to the Rupert basin, where an area of 300 square miles was flooded to an average depth of 50 feet. Floodwater was released from the Rupert basin via the Snake River, which even then must have occupied a canyon much like the present one, and it also was released by simultaneous overflow into an upland channel that rejoined the canyon near Twin Falls, 30 miles downstream. At this junction, an anomalously broad canyon segment 14 miles long was apparently greatly enlarged by flood erosion. This chaotically eroded stretch of canyon now presents a weird landscape of scabland, cataracts, and spillway alcoves.

The Snake River canyon in the reach 105 miles below Twin Falls is a trench 500–600 feet deep made up of basins carved from soft deposits and of constricted segments cut into basalt. The narrow places impeded flow and impounded floodwater in basins at Melon Valley, Hagerman, King Hill, Glenns Ferry, Hammett, Indian Cove, and Eagle Cove, which therefore acted as sediment traps for Melon Gravel. A particularly narrow constriction near Crane Falls at the downstream end of this reach impounded water 300 feet deep that extended 45 miles upstream as a nearly continuous lake to the head of the King Hill basin. Because the King Hill basin is situated where the Bonneville Flood first entered relatively slack water, it holds more than half of the Melon Gravel that was flushed down the canyon.

Not all the floodwater could pass the narrow canyon at Crane Falls, and some water spilled westward along an upland channel 7 miles long that emptied into another temporary lake in the Grand View basin, which covered 150 square miles to a depth of as great as 325 feet. The lake at Grand View was the final trap for flood debris from sources upstream.

Floodwater in the Grand View basin was impounded by several miles of narrow canyon that includes the flumelike neck near Swan Falls used by Jenkins to calculate the probable maximum discharge. From here, the flood emerged into a wide basin that surrounds Walters Ferry where another enormous heap of Melon Gravel was deposited. Below Walters Ferry the Snake River canyon widens into a broad lowland that continues many miles downstream. Signs of the Bonneville Flood are not evident in this lowland, but flood debris is again found farther on in Hells Canyon.

Comparison of the volume of Melon Gravel with the size of the Snake River canyon upstream provides a basis for estimating the probable amount of erosion caused by the Bonneville Flood. The volume of gravel from Twin Falls downstream to Grand View is about six-tenths of a cubic mile. Flood erosion along the 14 miles of anomalously enlarged canyon already mentioned near Twin Falls may have alone produced from one-third to one-half of a cubic mile of flood debris. Thus, the canyon near Twin Falls was the major source of the Melon Gravel. The remainder was produced mostly by erosion along constricted canyon segments downstream, but simple arithmetic indicates that this downstream reach could not have been much enlarged by flood erosion, and its present appearance must closely resemble its aspect prior to the Bonneville Flood—except as modified by deposits of Melon Gravel.

When flood velocities estimated from the size of the boulders in Melon Gravel along the Snake River canyon are multiplied by cross-sectional areas of narrow stretches of canyon inferred from the flood profile, the indicated discharges are comparable to the amount calculated at the flumelike neck near Swan Falls. For example, 4-foot boulders at Melon Valley indicate a velocity of 17 fps (feet per second) and a discharge of 17 million cfs (cubic feet per second)—that is, four-tenths of a cubic mile per hour; and 10-foot boulders between Bliss and King Hill indicate a velocity of 24 fps and a discharge of 14 million cfs—or one-third of a cubic mile per hour. Boulders in Melon Gravel may be rather accurate indicators of the velocity of flow.

Although the Bonneville Flood greatly exceeded the ordinary behavior of rivers, its violence can be partly comprehended by comparison with other catastrophic floods of modern times. The hydrologic effects of several great historic floods are briefly reviewed: those of Gohna, India; Great Indus Flood; Gros Ventre, Wyo.; Lake Issyk, U.S.S.R.; St. Francis Dam, Calif.; Vaiont Reservoir, Italy; various jökulhlaups (glacier bursts) in Iceland; and catastrophic floods from ice-dammed lakes.

INTRODUCTION

BACKGROUND OF STUDY

Pleistocene Lake Bonneville, at one time in its early history, spilled northward at Red Rock Pass near Preston, Idaho, and suddenly released an enormous volume of water onto the Snake River Plain (fig. 1). Evidence of this catastrophe, known as the Bonneville Flood,[1] was discovered by Gilbert (1878) during his pioneer study of ancient Lake Bonneville, but the wide-reaching effects of the immense discharge downstream along the Snake River were not recognized until 1954, when they were explained to me by Howard A. Powers, of the U.S. Geological Survey. Subsequent fieldwork by several geologists has shown tht Marsh Creek Valley immediately downstream from Red Rock Pass was flooded from wall to wall, as were large parts of the upper Snake River Plain—notably an area near American Falls and a basin that surrounds Rupert. Farther downstream, the 200-mile canyon of the Snake River was flooded to a depth of 300 feet. Spectacular erosion in the form of abandoned channels, spillways, and scabland marks the flood path downstream to Twin Falls, and huge bars of boulders and sand that indicate a former stream of extraordinary size litter the canyon farther west. This report is focused on the route followed by the flood from the upper Snake River Plain to the canyon head near Twin Falls and on the stretch of canyon extending 200 miles downstream to Givens Hot Springs (fig. 2).

Geologists first explained gigantic boulders in the Snake River canyon as basalt blocks worn by water (Russell, 1902, pl. 25*B*),[2] and then as debris eroded from nearby lava dams (Stearns, 1936, p. 441-442; Stearns and others, 1938, p. 89), but the boulders are now identified as impressive signs of havoc caused by water discharged from Lake Bonneville (Malde, 1960).

When Gilbert (1890, p. 175–177) described effects of the voluminous outflow along the first several miles below Red Rock Pass, he referred to the effluent as the Bonneville River, and this usage was adopted by Trimble and Carr (1961a) when they described the outflow near Pocatello in the upper Snake River Plain. However, to emphasize the catastrophic results of peak discharge, which lasted only a short time, I refer to the sudden outflow as the Bonneville Flood.

[1] The name "Bonneville Flood" was first used in a guidebook prepared for the 7th INQUA Congress (Richmond and others, 1965, p. 98), which included as part of the source material excerpts from a preliminary manuscript of this report.

[2] This photograph (I. C. Russell, 757) in the field records of the U.S. Geological Survey, Denver, Colo., bears Russell's caption, "Blocks of lava rounded by the river; not transported by the river or by the glacier. Snake River, Idaho."

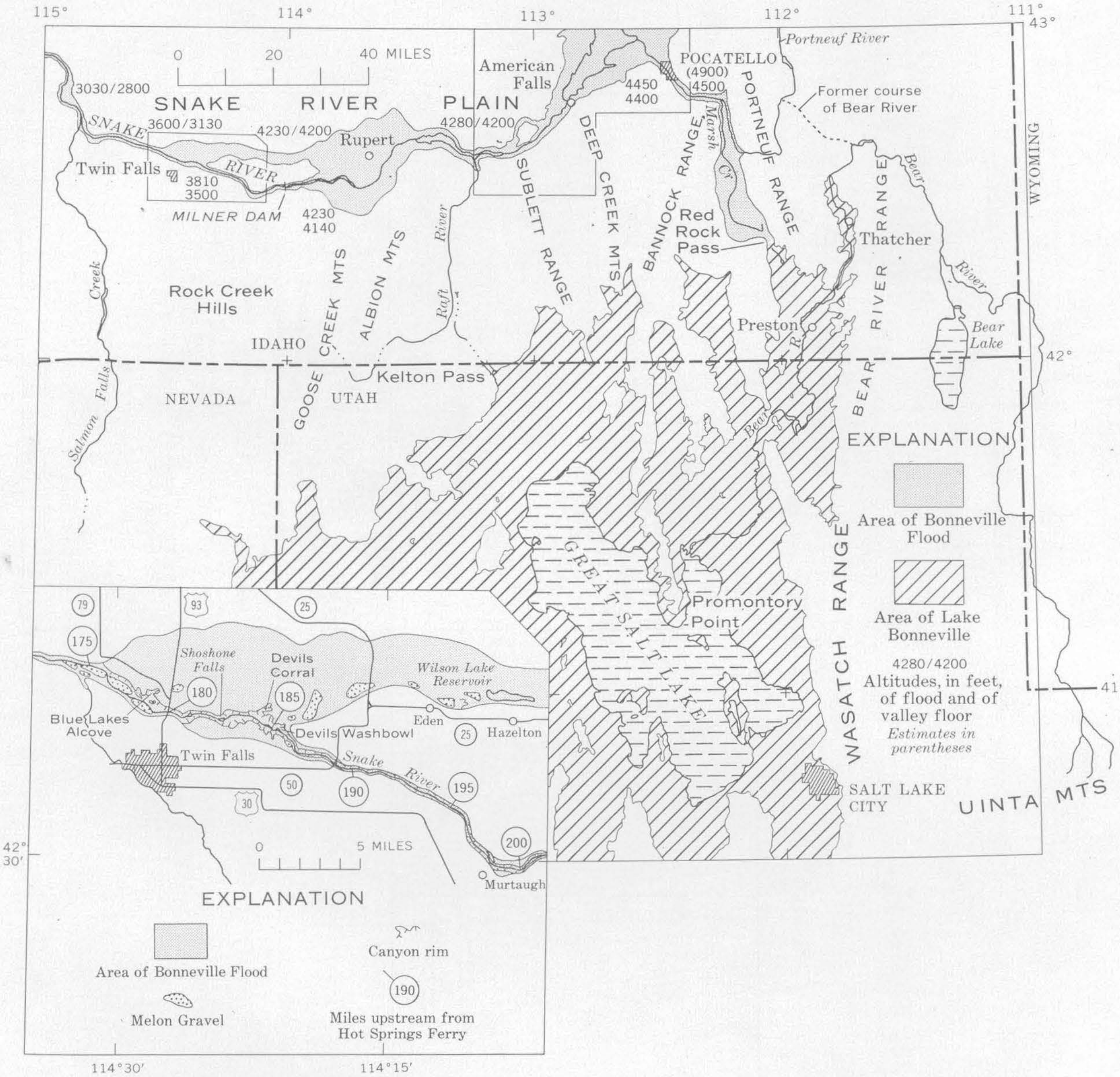
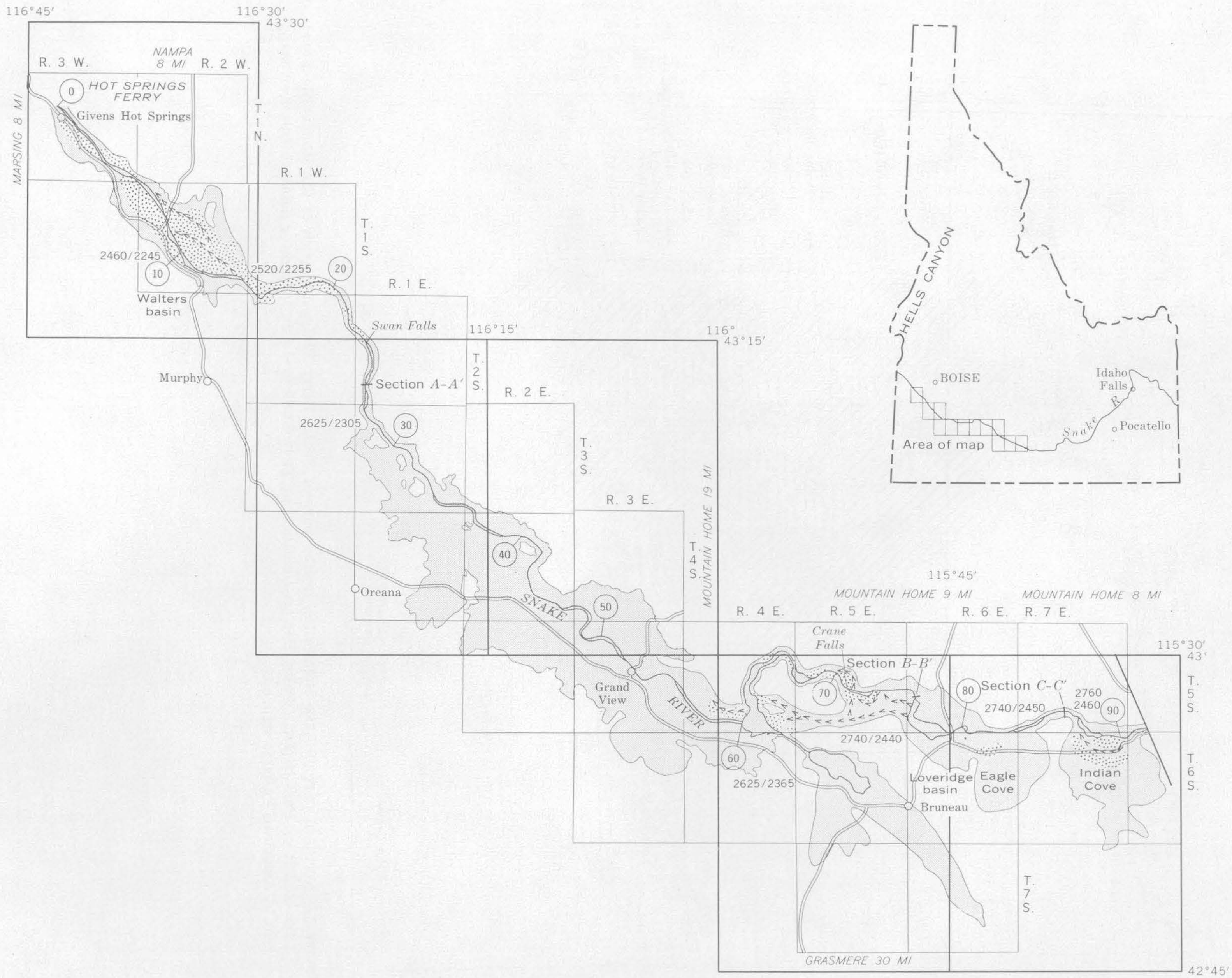


Figure 1.—Northern part of Lake Bonneville, nearby part of Snake River Plain, and path of the Bonneville Flood from Red Rock Pass to Twin Falls. The area outlined at Twin Falls is shown in greater detail in the inset map; that at American Falls, in figure 10.


116°45'
116°30'
43°30'
R. 3 W.
NAMPA 8 MI
R. 2 W.
MARSING 8 MI
HOT SPRINGS FERRY
Givens Hot Springs
T. 1 N.
R. 1 W.
T. 1 S.
2460/2245
2520/2255
Walters basin
R. 1 E.
Swan Falls
116°15'
116°
43°15'
Murphy
Section A-A'
T. 2 S.
R. 2 E.
2625/2305
T. 3 S.
R. 3 E.
T. 4 S.
MOUNTAIN HOME 19 MI
Oreana
SNAKE
RIVER
Grand View
115°45'
MOUNTAIN HOME 9 MI
MOUNTAIN HOME 8 MI
R. 4 E.
R. 5 E.
R. 6 E.
R. 7 E.
Crane Falls
Section B-B'
Section C-C'
115°30'
43°
T. 5 S.
2760
2460
2740/2450
2740/2440
2625/2365
Loveridge basin
Eagle Cove
Indian Cove
Bruneau
T. 6 S.
T. 7 S.
GRASMERE 30 MI
42°45'
0
10
20
30
40
50
60
70
80
90
HELLS CANYON
BOISE
Idaho Falls
Snake R.
Pocatello
Area of map

289-124 O—68——2

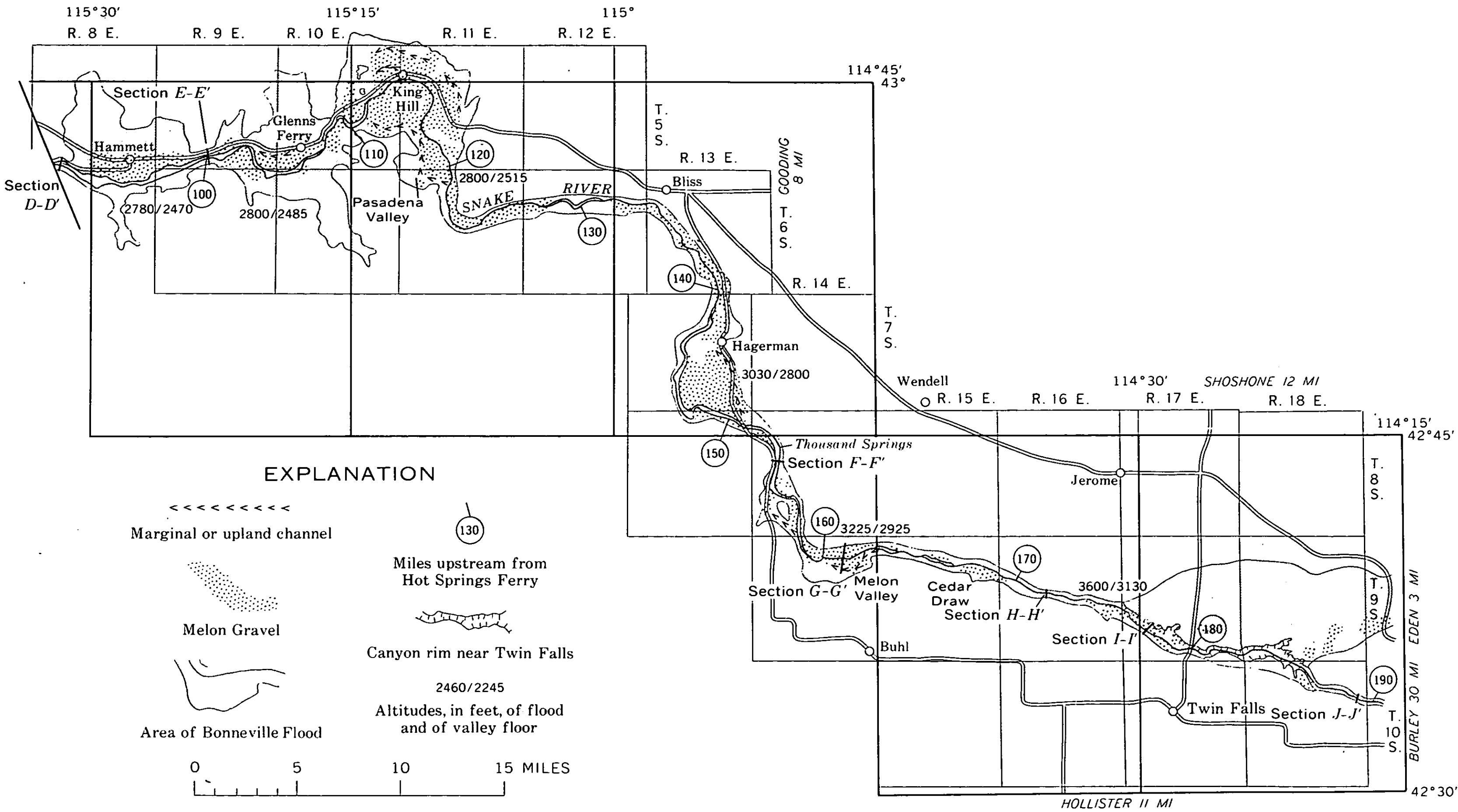


Figure 2.—Snake River below Twin Falls, deposits of Melon Gravel, marginal channels, area of Bonneville Flood, heights of floodwater, and locations of sections. River mileage, which is measured upstream from the Hot Springs Ferry, is based on the survey of Marshall (1914).

The observations reported here were made during the course of regional geologic studies, beginning in 1954 (Malde and Powers, 1962). The geology of the area near Pocatello where the flood debouched onto the Snake River Plain was mapped by Trimble and Carr (1961b), and part of the flood path below Twin Falls was also mapped by Malde, Powers, and Marshall (1963). Practically all the flood area is covered by detailed topographic maps.

ACKNOWLEDGMENTS

Before my fieldwork in the Snake River Plain began, H. A. Powers called my attention to the significance of boulder deposits near Hagerman and pointed out their catastrophic origin. In 1955, amused by a whimsical billboard that advertised one patch of boulders as "petrified watermelons," we (Malde and Powers, 1962, p. 1216) applied to them the descriptive geologic name, Melon Gravel, which has since become one of many evocative terms in stratigraphic nomenclature. Later, E. G. Crosthwaite, who was doing ground-water studies in the upper Snake River Plain, told me about the role of the Rupert basin as a "regulating reservoir" along the flood path, and he described important features along an upland channel between Rupert and Twin Falls. Meanwhile, D. E. Trimble and W. J. Carr were examining effects of the Bonneville Flood between Pocatello and American Falls, and their observations enlarged my perspective. In 1962, those who joined me on a field trip for the Friends of the Pleistocene (Rocky Mountain Section) along the flood path downstream from Twin Falls reviewed my analysis of the flood; accordingly, my understanding improved. Lastly, participants in the 1965 INQUA Field Conference E—most of them from foreign countries—contributed provocative ideas from their diverse experience. Of these participants, I am especially indebted to Roald Fryxell and G. M. Richmond, who brought to the Snake River Plain their intimate knowledge of Pleistocene floods in eastern Washington.

SUMMARY OF FLOOD PATH

The Bonneville Flood mostly occupied the same canyons and valleys that exist today, but it modified them by causing extensive erosion and by depositing great piles of flood debris. It left a vivid record of its cataclysmic passage. The havoc produced by the flood was influenced to a considerable extent by local physiographic factors and by the rocks found along the way. The Snake River is one of the steepest large streams in North America, and descends in altitude from 4,400 feet at Pocatello to 2,200 feet at Givens Hot Springs, 300 miles downstream. Although interspersed with relatively tranquil stretches, this steep gradient undoubtedly added to the flood force and velocity. The Bonneville Flood is best understood by a brief tracing of its path downstream from Red Rock Pass.

Features along the path in Marsh Creek Valley, where the flood spread from wall to wall, are being studied by R. C. Bright and Meyer Rubin (see Richmond and others, 1965, p. 103–106). It is noteworthy that the flood along this stretch was impeded by the Portneuf Narrows, a canyon neck 45 miles downstream from Red Rock Pass. As indicated by the calculated discharge (see p. 12), the maximum flood probably was at least 400 feet deep at this place (see altitudes in fig. 1), and the floodwater some distance upstream was relatively tranquil during peak flow. Nonetheless, the size of boulders in flood debris along Marsh Creek Valley indicate a velocity of 25 fps (feet per second) (Richmond and others, 1965, p. 106).

From the Portneuf Narrows the flood fell rapidly to the Snake River Plain at Pocatello where it entered shallow water of an existing lake held by a basalt dam near American Falls, 30 miles downstream; here it dumped a delta of bouldery debris on the lake bottom. The size of this debris ranges from boulders as large as 8 feet at Pocatello to cobbles 10 miles downstream, owing to the spread of floodwater in the lake. (See fig. 10.) Discharge of floodwater from this lake over and around the basalt dam cut several channels and spillways on the upland and along the Snake River. As erosion progressed, floodwater became lower, and terraces were cut on the delta. Molluscan fossils from the highest terrace were presumably living when the flood began and are dated by radiocarbon at 29,700±1,000 years (Trimble and Carr, 1961b, p. 1746; sample W–731).

Beyond the maze of channels and spillways below American Falls, the flood descended in a broad swath along the Snake River to the Rupert basin, where it covered 300 square miles to an average depth of 50 feet. Floodwater escaped from this basin mostly through a basalt gorge at the head of the Snake River canyon—at this place a scoured trench 20 miles long of remarkably constant width and depth (about 1,100 by 325 ft)—but floodwater also escaped by simultaneous overflow into an upland channel that rejoined the canyon at Twin Falls, 30 miles downstream. (See inset map in fig. 1.) At this junction, apparently because of flood erosion on a grand scale, a canyon segment more than 10 miles long is anomalously broad and deep, as much as 5,000 by 500 feet. The southern rim has a ragged edge along several miles, and the northern rim where floodwater debouched from the upland channel is intricately dissected by numerous spillway alcoves. A series of spectacular "underfit" waterfalls (for example, scenic Shoshone Falls) occurs along the canyon floor. Bordering scabland demonstrates that this wide stretch of canyon was for a time virtually brimful.

The amount of flood erosion near Twin Falls may be roughly estimated by comparing the size of the enlarged part of the canyon with that of the canyon immediately above and below. (See p. 44.) For the part from mile 175 to 189, where effects of erosion are obvious, the flood removed from one-fourth to one-third of a cubic mile of basalt. Considered as gravel having 25-percent porosity, this material would have produced from one-third to nearly one-half a cubic mile of flood debris. An indeterminate amount of basalt—but undoubtedly a much smaller quantity—was eroded from the 20 miles of canyon upstream.

In the next 105 miles downstream from Twin Falls, the Bonneville Flood was entirely confined to the Snake River canyon—a trench 500–600 feet deep of variable width made up of basins carved from soft deposits and of constricted segments cut into basalt (fig. 2). The narrow places impeded flow and impounded floodwater in basins at Melon Valley, Hagerman, King Hill, Glenns Ferry, Hammett, Indian Cove, and Eagle Cove, which therefore acted as traps for basaltic flood debris flushed down the canyon. This debris—the Melon Gravel—was deposited in the basins as gigantic bars, some of them several miles long and nearly 300 feet high. The bars consist of chaotic mixtures of boulders and sand arranged in crossbeds of phenomenal scale. They mostly lie midway between the canyon walls from which they are separated by marginal channels as deep as 150 feet. Basalt boulders, commonly larger than 5 feet, are conspicuous on bars just below constrictions; but flood debris in wider places a mile or two farther downstream is dominantly basaltic sand—although nonetheless bouldery. The boulders generally can be identified as having come from outcrops at narrow places not more than a few miles upstream.

Because the basins were effective traps for Melon Gravel and because subsequent erosion of this debris has been trivial, the volume of Melon Gravel roughly measures the amount of flood erosion. (See table 4, p. 45.) For the stretch between Twin Falls and Eagle Cove, this volume is a little more than half a cubic mile, of which more than one-half was deposited in the basin at King Hill—the farthest upstream reach of relatively slack floodwater. (See profile of Bonneville Flood, fig. 3.)

A particularly narrow constriction at mile 75 near Crane Falls impounded water 300 feet deep upstream and caused some floodwater to spill across the upland and empty into another temporary lake in the Grand View basin. Deltaic debris at the spillway mouth (mile 61 in fig. 2) shows that the lake at Grand View was as deep as 325 feet and therefore covered 150 square miles. The Grand View basin contains only scant amounts of Melon Gravel and must have been the final trap for flood debris from sources upstream.

From the Grand View basin the Bonneville Flood passed through several miles of narrow canyon, including a flumelike neck near Swan Falls used by C. T. Jenkins to calculate a probable maximum discharge of about 15 million cfs (cubic feet per second)—that is, more than one-third cubic mile per hour (see p. 12)—and emerged into the Walters basin where another enormous heap of Melon Gravel was deposited.

Not far below the Walters basin, basalt rimrock along the Snake River disappears, the topography becomes subdued, and the canyon widens into a broad lowland that continues many miles downstream. Signs of the Bonneville Flood are not evident in this lowland, but flood debris is again found farther on in Hells Canyon (Stearns, 1962).

GLACIAL AND PLUVIAL STRATIGRAPHY

In the discussion that follows, it is necessary to refer to lake levels and deposits of Lake Bonneville and to their correlation with glacial episodes. The pertinent relations have been recently reviewed (Morrison, 1965; Morrison and Frye, 1965) and are summarized in the chart on page 9. The lake levels along the Wasatch Range at altitudes of about 4,470, 4,800, and 5,135 feet are referred to as the Stansbury, Provo, and Bonneville shorelines, respectively. Because of differential warping resulting from isostatic rebound after loss of lake water, these shorelines differ in altitude at Red Rock Pass.

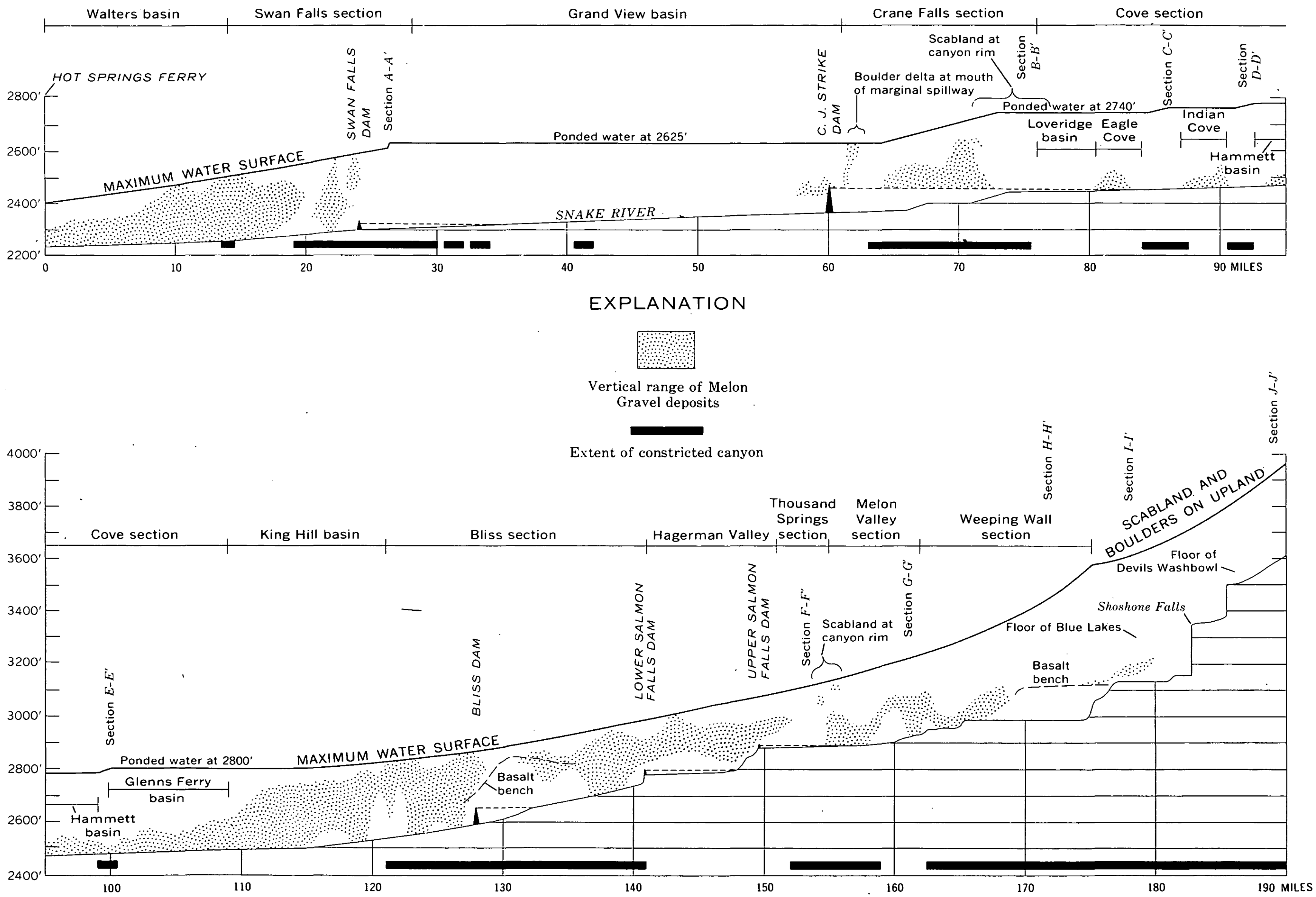


FIGURE 3.—Profile of Snake River and of Bonneville Flood at highest stage. Sections are shown in figure 13, except *G–G'*, which is shown in figure 17.

Glacial stratigraphy		Lake Bonneville: Stratigraphy	Altitude of lake, in feet-- Along Wasatch Range (approximate)	Altitude of lake, in feet-- At Red Rock Pass
Neoglaciation		Subaerial and shallow-lake sediments	4250	Not present.
	Midvale soil	Midvale soil		
Pinedale Glaciation	Upper till	Draper Formation	4410 4470 Stansbury shoreline 4770	Not present.
Pinedale Glaciation	Graniteville soil	Graniteville soil		
Pinedale Glaciation	Middle till	Bonneville Formation: Upper member	4800 Provo shoreline 5135 Bonneville shoreline	4780 5085
Pinedale Glaciation	Lower till	Bonneville Formation: White marl member	Not yet determined	Not known.
Promontory soil		Promontory soil		
Bull Lake Glaciation		Alpine Formation	5100	Not known.

SOURCE

Red Rock Pass, the lowest place on the rim of the Bonneville basin, is the only possible source of the Bonneville Flood, as shown by numerous geologic effects of catastrophic discharge found downstream and by the absence of such effects along other tributaries of the Snake River. In the lower end of Marsh Creek Valley below Red Rock Pass, Gilbert long ago (1890, p. 175–177) described the eroded surface of a lava flow that was scoured and channeled by the flood. A drainage connection at Red Rock Pass is also suggested by certain endemic fishes shared by the Bonneville basin and the Snake River above American Falls (Hubbs and Miller, 1948, p. 30–31; Miller, 1958, p. 211–213), but this common heritage may stem instead either from a connection later than the Bonneville Flood or from a more complex route that involved a former connection between Bear Lake and the Snake River (Miller, 1965, p. 577–578).

Red Rock Pass is now graded to a level near a conspicuous shoreline of Lake Bonneville called the Provo shoreline (4,780 ft alt)—or possible to the "Provo 2" shoreline recognized at about this altitude farther south along the Wasatch Range. (See Morrison, 1965, p. 276.) The pass is cut in Paleozoic shale, limestone, and dolomite so as to form a narrow gap 2 miles long (Williams, 1962, p. 143–145). At one time, Red Rock Pass was several hundred feet higher, at the level of the Bonneville shoreline (5,085 ft alt, according to a spirit-level measurement by Gilbert). Jagged remnants of Paleozoic rocks up to this altitude in the Pass suggest that the Bonneville shoreline was controlled by this sill of resistant rocks. As will be explained below, rapid discharge at a level above the Bonneville shoreline—presumably by sudden removal of unconsolidated surficial material—apparently accounts for the catastrophic character of the Bonneville Flood. When the lake level fell to bedrock at the Bonneville shoreline, the resistant rocks impeded erosion, and discharge dwindled. Overflow at a later time gradually eroded Red Rock Pass to the Provo level.

Kelton Pass (5,305 ft alt), a somewhat higher drainage divide between the Bonneville basin and the Snake River (fig. 1), is about 115 feet above the highest nearby Bonneville shoreline (5,190 ft alt, according to Crittenden, 1963, fig. 3). Kelton Pass does not appear eroded, and no sign of voluminous floodwater can be seen in the Raft River valley to the north, which would have received any spillover from this divide.

In the present headwaters of the Snake River, Jackson Hole in Wyoming is the only basin from which a large discharge might account for some features attributed to the Bonneville Flood, but recent geomorphic studies in Jackson Hole yield no evidence of sudden release of large volumes of water during the late Pleistocene (John de la Montagne and J. D. Love, oral commun., 1958), and discharge from Jackson Hole could not account for the effects of catastrophic outflow found in Marsh Creek Valley or for the boulder deposits at Pocatello.

AGE

The Bonneville Flood was one of the most recent geologic events along the Snake River and is surely of late Pleistocene age. The only notable younger deposits along the river, other than those of the flood plain, are discontinuous patches of stream gravel, presumably contemporaneous with mountain glaciation. The flood deposits are moderately weathered at the surface and have a friable calcareous soil profile about 4–6 feet thick, but they are otherwise rather fresh and lack the deep profiles of weathering and thick layers of hard caliche that characterize older Pleistocene deposits in the uplands. Exposed boulders are stained brown and have exfoliating rinds about half an inch thick. Their surfaces are commonly grooved and polished by the action of windblown sand. Evidently the flood deposits have been exposed to weather for a considerable time. (See remarks on p. 11 about correlation of the soil profile.)

Current information allows some latitude in dating the Bonneville Flood, but an estimate of age can be deduced from the flood's inferred dependence on certain geologic events pertaining to the Bear River. This stream rises in the Uinta Mountains (fig. 1) and accounts for more than 43 percent of the present inflow to Great Salt Lake. Diversion of the Bear River into the Bonneville basin, first discussed by Gilbert (1890, p. 218–220, 263), was probably responsible for overflow of Lake Bonneville at Red Rock Pass and, hence, caused the flood. The details of the Bear River diversion have been worked out by R. C. Bright (1963), and they suggested to him that spillover at Red Rock Pass occurred during deposition of the Bonneville Formation about 18,000 years ago. In this view he is joined by Meyer Rubin. (See Richmond and others, 1965, p. 105–106.) D. E. Trimble and I, however, as well as some of our colleagues, believe that the available evidence points more strongly to spillover in Alpine time, probably about 30,000 years ago. This difference in opinion arises partly from the complicated history of the Bear River revealed by Bright's study and partly from radiocarbon dates and geologic knowledge gathered by Bright and other workers along the flood path downstream from Red Rock Pass. The pertinent relations are as follows.

Prior to 34,000 years ago, as indicated by radiocarbon dates to be mentioned shortly, the Bear River flowed from Bear Lake to the Snake River Plain at Pocatello. The river followed the present route of the lower Portneuf River. (See dotted line in fig. 1.) Subsequently, according to Bright, the ancestral Portneuf was dammed by several basaltic lava flows (and probably by faulting), and the Portneuf and Bear Rivers were impounded in a basin at Thatcher. These events formed a lake—Lake Thatcher. Later lava flows, of which one or more descended the Portneuf valley nearly to Pocatello, returned the Portneuf River to its former route and at various times may have permitted the Bear River to discharge westward via Lake Thatcher. Organic material in a soil under one of these lava flows in lower Marsh Creek Valley, near the Portneuf, yields various radiocarbon dates—35,000±3,000 years (sample W–1177); 33,000±1,600 years (W–1121); 30,000±2,000 years (W – 1329); and 25,000±2,000 years (W–1334)—and the lava surface displays abundant signs of erosion by the Bonneville Flood. Mollusks from the lower part of lake beds probably impounded behind the lava in Marsh Creek Valley yield a radiocarbon date of 32,500±1,500 years (W–1221). At Thatcher, several collections of mollusks from deposits of Lake Thatcher range in radiocarbon age from 33,000±1,600 years (sample W–1128) to 27,000±900 years (W–1125). The similarity in age ranges indicates that eruption of the lava and filling of Lake Thatcher were approximately contemporaneous. Eventually, successive lava flows between the Bear and the Portneuf Rivers built a barrier higher than the south rim of Lake Thatcher (5,445 ft alt); Lake Thatcher then spilled southward across a quartzite divide into the Bonneville basin. Downcutting at this spillway ultimately formed a gorge with a floor at an altitude of 4,600 feet, which drained Lake Thatcher and allowed erosion of the lake deposits. By this time, Lake Bonneville must have been dry or at a low level. A subsequent rise of Lake Bonneville deposited beds of the Bonneville Formation on eroded deposits of Lake Thatcher, and correlative beds near the Bear River outlet are dated 18,900±500 years (sample W–982). Bright and Rubin believe that this rise of Lake Bonneville, not a rise that may have been caused by initial capture of the Bear River, was responsible for overflow at Red Rock Pass. Thus, they estimate the age of the Bonneville Flood at about 18,000 years.

To me, the evidence concerning diversion of the Bear River points simply to its initial capture as the cause of spillover at Red Rock Pass. If the radiocarbon dates are taken literally, overflow of Lake Thatcher could have been as recent as 27,000 years ago, as Bright (1963) accepts; but if one or two anomalously young dates are discounted as aberrant, the dates accord with overflow about 30,000 years ago. (It was this suddenly increased inflow, of course, that accounts for spillover of Lake Bonneville, and not the meager water supplied by Lake Thatcher.) This explanation ties one geologic event (the Bonneville Flood) to the greatly augmented inflow brought by the Bear River, for which the geologic effects are otherwise either problematic or invisible (Morrison, 1965, p. 276). It also lengthens the time available for the cutting of the outlet of Lake Thatcher—a gorge in quartzite more than 800 feet deep and several miles long. However, if Lake Bonneville initially overflowed 30,000 years ago in Alpine time, the lake level thereafter must have soon subsided (so as to account for downcutting at the outlet of Lake Thatcher and for the formation of the Promontory Soil at low level in the Bonneville basin). This circumstance suggests that lake level was influenced by other factors in addition to capture of the Bear River. That is, the augmented inflow brought by the Bear River could not alone have accounted for both a rapid rise in lake level and a subsequent subsidence. The additional factors that influenced the regimen of Lake Bonneville at time of spillover were undoubtedly effects of regional climate, and perhaps responses to climatic change, but these factors are as yet unknown. Nonetheless, whatever else caused Lake Bonneville to overflow and then subside, a 30,000-year age for the Bonneville Flood accords with information collected along the flood path below Red Rock Pass.

At American Falls a minimum age for the Bonneville Flood is given by a radiocarbon date of 29,700 ± 1,000 years (sample W-731) for mollusks from an alluvial terrace somewhat younger than the maximum flood, which probably formed as the flood waned and diminished in height (Trimble and Carr, 1961b, p. 1746). Although this date stands unsupported by others, it pertains to the only sample intimately tied to the flood deposits and must be considered in any reckoning of age. If the history of the Bear River is taken into account and if overflow at Red Rock Pass is assumed to coincide with the capture of Bear River via spillover of Lake Thatcher, the radiocarbon dates already mentioned for lavas in Marsh Creek Valley and for mollusks in Lake Thatcher do not generally contradict the date obtained at American Falls.

Two other matters indicative of antiquity for the Bonneville Flood must be mentioned, even though difficult to evaluate. First, I judge that the calcareous soil profile prevalent on flood debris along the Snake River resembles in thickness and degree of development, as well as in contrast to other soils in this region, the Promontory Soil formed on the Alpine Formation in the Bonneville basin. At a depth of 3 feet below yellowish-brown and weakly calcareous material of the B horizon is about 1½ feet of strongly calcareous soil that exhibits a platy structure marked by irregular plates of firm caliche. Visible carbonate in friable subsoil extends to a depth of more than 6 feet. Second, D. E. Trimble (oral commun., 1964) has observed on the lava devastated by the Bonneville Flood in lower Marsh Creek Valley a pattern of soil mounds comparable to patterned ground in the western Snake River Plain (Malde, 1964; Fosberg, 1965), which I attribute to late Pleistocene periglacial climate. If these mounds indeed formed in response to cold climate, it seems likely that they date from the time of Pinedale Glaciation and that the scoured surface produced by the flood is correspondingly older.

Whatever the age assigned to the Bonneville Flood, geologists now agree that it was undoubtedly older than the formation of the Bonneville shoreline—a level later controlled by the height of resistant bedrock in Red Rock Pass. Bright and Rubin (in Richmond and others, 1965, p. 106) found wave-washed debris and evidence of scour 30 feet above the Bonneville shoreline at Red Rock Pass. These features are obviously attributable to initial overflow. The true height of overflow is not determinable, but it could have been 100 feet above the Bonneville shoreline. (See p. 12.) Overflow may have been caused by sudden failure of an alluvial barrier, as Gilbert (1890, p. 175–178) supposed, but the actual deposit that formerly blocked the pass has never been identified. Probably it was entirely removed by the catastrophic outflow, and Lake Bonneville was thus drastically lowered—presumably as far as the bedrock lip at the Bonneville shoreline. Erosion thereafter would have been at a much slower rate and not of catastrophic magnitude. If follows that downcutting to the Provo shoreline, which was accomplished by the wearing away of hard rocks in Red Rock Pass about 13,500 years ago, according to radiocarbon dates reviewed by Morrison and Frye (1965, p. 20–24), was in no way responsible for the Bonneville Flood. This conclusion differs from a long-standing idea of Gilbert that erosion of Red Rock Pass to the Provo shoreline caused the flood. Not surprisingly, because of the frustrating paucity of relevant geology at Red Rock Pass, the present understanding of the age of the flood has been largely learned by diligent search elsewhere—chiefly by R. C. Bright and D. E. Trimble.

MAGNITUDE OF FLOOD

The enormous size of depositional and erosional features produced by the Bonneville Flood imply a peak discharge of extraordinary volume. The maximum discharge can be estimated from computed flow through certain constricted segments in the canyon of the Snake River, by use of standard hydraulic formulas.

Stearns (1962) calculated a peak discharge of 10 million cfs at Brownlee damsite near Homestead, Oreg., where the flood was 410 feet deep (that is, 290 ft above present river level), and where the canyon is 1,400 feet wide. The method of calculation is not stated, but his figure is comparable to that computed from the Manning equation. (See table 2, p. 25.)

The Snake River canyon below Twin Falls has many constricted segments that flowed deep with water during the flood (figs. 2, 3), and any of these would give a measure of discharge. Canyon constrictions cut into basalt near Swan Falls, however, at miles 26 and 28, (the mileage is measured upstream from Hot Springs Ferry, as shown in fig. 2) give an unusual opportunity for calculating maximum discharge by the critical-depth method. (See fig. 13, section *A–A′* at mile 26.) As will be explained (p. 42), this series of constrictions impeded flow and impounded floodwater 325 feet deep upstream (2,625 ft alt). Because the canyon widens downstream and no further major constrictions occur, there was virtually no backwater from downstream sources, and conditions for flow at critical depth were apparently satisfied. Boulders as much as 6 feet in diameter at an altitude of 2,575 feet about 2 miles farther downstream (mile 23½ at Swan Falls) establish a tailwater altitude. In brief, the Snake River canyon between miles 26 and 28 acted as the throat of a gigantic venturi flume, a device commonly used to measure discharge in channels. Assuming that the canyon now retains the shape acquired during passage of the flood and that it acted as a venturi flume, Clifford T. Jenkins, U.S. Geological Survey (oral commun., 1964) calculates a maximum discharge of from 12.2 to 16.3 million cfs—the range being determined by the limiting values adopted for channel roughness and friction losses. The most likely discharge was about 15 million cfs, or more than one-third cubic mile per hour, which is about three times the average discharge of the Amazon.

The maximum historic discharge in the upper Snake River was recorded at Idaho Falls in early June 1894 and amounted to 72,000 cfs (U.S. Geol. Survey, 1959, p. 44), or about one two-hundredths of peak discharge during the Bonneville Flood. The destructive flood caused by rupture of the Gros Ventre landslide in the upper Snake River basin (Alden, 1928) amounted to 60,000 cfs when it reached Idaho Falls.

DURATION

The duration of the Bonneville Flood can be judged from the discharge capacity of canyon sections along the Snake River and from the probable volume of water available in Lake Bonneville. Although the maximum probable discharge was about 15 million cfs, the average discharge must have been much less. The probable volume of available water is subject to more uncertainty. Radiocarbon age determinations and the geologic relations just described indicate that Red Rock Pass was lowered during the flood no farther than the Bonneville shoreline, probably by rapid removal of surficial material. The height of overflow has not been determined, but it could not have been more than 115 feet above the Bonneville level, otherwise overflow would have occurred at Kelton Pass (p. 9). According to Williams (1962), a pass at 5,180 feet altitude (thus 95 ft above the Bonneville shoreline) a mile east of Red Rock Pass "shows no evidence of outflow." A duration of flow based on lake lowering of not more than 100 feet therefore seems reasonable. The corresponding volume is readily calculated from published hypsometric data (Eardley and others, 1957, p. 1143–1145):

Altitude of lake (feet)	*Surface area (square miles)*	*(acres)*
5,235± (spillover)	[1] 21,200	13.57 × 10⁶
[2] 5,135± (Bonneville level)	[2] 19,750	12.64 × 10⁶

[1] Estimated from data of Eardley, Gvosdetsky, and Marsell (1957).
[2] Gilbert's average altitude of 5,135 ft for the Bonneville shoreline is used although the altitude of the shoreline throughout the basin owing to isostatic deformation (Crittenden, 1963). At Red Rock Pass the Bonneville shoreline is at 5,085 ft alt, according to Gilbert.

From the formula of Eardley, Gvosdetsky, and Marsell (1957, p. 1143)—(area at level 5,135 × 100 ft) + (difference in area at levels 5,235 and 5,135 × 100 ft, divided by 2½)—the volume of water between the Bonneville shoreline and a spillway 100 feet higher would have been 1.3 billion acre-feet, or about 380 cubic miles. Thus, a continuous discharge of 15 million cfs—that is, a little more than one-third cubic mile per hour—could have been maintained 6 weeks. A discharge of 1.8 million cfs would have lasted about a year.

An erroneously long duration of flow based on a misinterpretation of Eardley's data was calculated by Stearns (1962), who further assumed mistakenly that the water was discharged between the Bonneville and Provo shorelines, rather than entirely above the Bonneville.

Gilbert (1890, p. 177) estimated the duration by assuming that erosion features on basalt 22 miles below Red Rock Pass—part of the lava that diverted the Bear River—could be accounted for by a river approximately the size of the Niagara: 200,000 cfs. Gilbert also thought the discharge was from the interval between the Bonneville and Provo levels, and he thus estimated the duration of discharge as somewhat less than 25 years.

Lakes that discharge over earth barriers, as indicated by records mentioned later in this report, ordinarily release most of their water suddenly, and the flow thereafter rapidly diminishes. Because a flood wave becomes attenuated during travel downstream, a constricted section of canyon like that at Swan Falls may not provide a reliable measure of peak discharge at the source, which could be considerably greater. Discharge from Lake Bonneville therefore may have been extraordinarily large at first—perhaps exceeding the rate measured downstream—but probably soon decreased.

For some lakes, however, discharge over an earth barrier is not excessively rapid, as shown by the history of Lake Tanganyika, east Africa. From the time of its discovery in 1854, Lake Tanganyika rose steadily until 1878, when it began to discharge over a dam of earth that had blocked the exit, the Lakuga River (Tison, 1949). In the next 7 years the lake dropped 9.5 meters to a new level, at which it stabilized. In an equivalent period before overflow, the lake rose 1.5 meters; thus, the total outflow was equal to a lowering of 11 meters. Because the area of the lake is 34,000 square kilometers (Hutchinson, 1957, p. 168), or 8.4 million acres, the amount discharged in the 7-year period was 300 million acre-feet, or about one-fourth of the volume possibly discharged from Lake Bonneville during the Bonneville Flood.

In the light of the above discussion, I infer that the major effects of the Bonneville Flood probably were produced in a few days (certainly in less than a month) and that voluminous discharge continued for at least a year.

Geologic studies now in progress at Red Rock Pass by R. C. Bright and Meyer Rubin can be expected to determine the probable configuration of the spillway during the Bonneville Flood, and hence will allow a calculation of maximum discharge based on hydraulic principles.

COMPARISON WITH LAST CATASTROPHIC FLOOD FROM GLACIAL LAKE MISSOULA, MONT.

The late Pleistocene flood from glacial Lake Missoula, Mont., first deduced by Pardee (1910 and 1942), far exceeded the Bonneville Flood in violence, although it was only a little greater in total volume. The present knowledge of this flood is discussed by Bretz, Smith, and Neff (1956, p. 1034–1042), by Bretz (1959), and by Richmond, Fryxell, Neff, and Weis (1965, p. 236, 239–240). Lake Missoula occupied the valley of the Clark Fork behind a dam formed by a lobe of the Cordilleran Ice Sheet. At the time of its sudden release by failure of the ice dam, Lake Missoula held 500 cubic miles of water, which escaped at an estimated peak discharge of 9½ cubic miles per hour—almost 30 times the rate computed for the Bonneville Flood. Thus, Lake Missoula probably emptied even more rapidly than Lake Bonneville.

DIAGNOSTIC DEPOSITIONAL AND EROSIONAL FEATURES

MELON GRAVEL

The Melon Gravel (Malde and Powers, 1962, p. 1216–1217) consists of deposits of boulders and sand left by the Bonneville Flood during its passage down the Snake River. The boulders are commonly 3 feet in diameter, but some well-rounded boulders measure 10 feet. Correlative deposits in the upper Snake River Plain attributed to the flood are known as the Michaud Gravel (Trimble and Carr, 1961b, p. 1742).

The Melon Gravel displays a multitude of lithologic and physiographic features that indicate torrential origin in rapidly moving deep water. Consisting almost entirely of basalt debris derived from local lava flows and piled in huge bars that partly fill the canyon to a depth as great as 300 feet, the Melon Gravel is the most easily recognized evidence of the catastrophic magnitude of the flood. The principal lithologic features that give the gravel its character, besides its distinctive basaltic composition and gigantic rounded boulders, are extremely poor sorting (mainly boulders and coarse sand, but no fine sand or silt), a general lack of horizontal bedding (but common occurrence of thick sets of inclined beds), and extraordinary variation in size of debris in local deposits (the maximum particle size decreases rapidly below canyon constrictions). The physiographic features of the Melon Gravel are equally distinctive: enormous streamlined bars veneered with boulders, usually at midcanyon locations; gravel crowded in local basins just below canyon constrictions; bars associated with marginal channels that separate the gravel from canyon walls; and tributary valleys obstructed by heaps of gravel. In these attributes of lithology and physiography the Melon Gravel matches in considerable detail the gravel bars in the channeled scabland of eastern Washington (Bretz and others, 1956), which were left by glacial rivers during catastrophic floods.

LITHOLOGY

Exposures in deep borrow pits and at numerous lesser outcrops show that the Melon Gravel is a thorough mixture of two principal components, boulders and coarse sand. Pebbles and finer sand are generally sparse. The best exposures are at excavations in gravel bars at the mouth of Cedar Draw (mile 168, fig. 2), Melon Valley (mile 161), the Union Pacific Railroad ballast pit (mile 109), and Walters Ferry (mile 8). These excavations expose thick sections of the gravel and belie the bouldery aspect presented at the surface by exhibiting large amounts of sand.

The boulders are almost all basalt—the only important hard material in the Snake River Plain—although rounded chunks of consolidated sedimentary material, ordinarily silt or diatomite, occur locally. Boulders of sedimentary material are especially evident in the railroad pit at mile 109 and at the upper end of the Grand View basin (Stearns, 1952), where floodwater was impounded in deep temporary lakes. The basalt boulders are typically very well rounded and obviously have been thoroughly rolled, tumbled, and abraded during their passage downstream (fig. 4). Rounding of boulders is conspicuous even though their source (determined by lithologic comparison) is only a few miles distant.

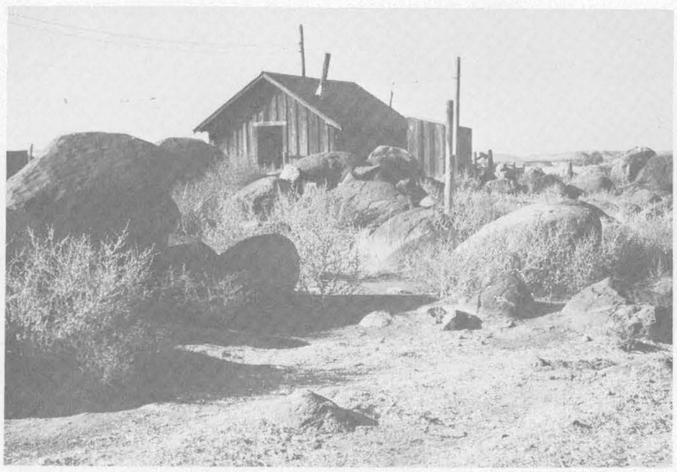


FIGURE 4.—Boulders on a bar of Melon Gravel 1½ miles south-southeast of Hagerman, Idaho. They are 150 feet above Snake River and 2½ miles east of the present channel. The boulders were washed from a basalt outcrop about 3 miles upstream.

The abundant coarse sand, consisting almost entirely of basalt fragments, is probably a product of abrasion of the boulders. This sand was evidently produced in great quantities in comparatively short distances of transport. Thus, even in the upper part of the canyon, at mile 168, a bar of Melon Gravel was built largely of basaltic sand. Basalt outcrops from which this sand was derived extend no farther than 40 miles upstream, and the sand therefore indicates rapid mechanical disaggregation of material moved by the flood.

These attributes of the Melon Gravel—mixed particle sizes, well-rounded boulders from nearby outcrops, and large quantities of locally derived sand—differ markedly from the character of load transported by ordinary streams and suggest abnormally large flow Hjulström, 1952; Fahnestock and Haushild, 1962).

Bedding is not conspicuous in the Melon Gravel, but deep excavations show crude sorting into contrasting layers of bouldery debris and cross-laminated sand. Lying generally at inclined attitudes, such layers form great sets of festoon crossbeds in courses 50 feet or more thick. At Melon Valley, in a pit at the downstream end of a gravel bar, beds dip downstream and toward the left and right banks (fig. 5). Gigantic crossbeds in sand are well exposed in the railroad pit (mile 109) and at Walters Ferry (mile 8). At the railroad pit (fig. 6), which is cut perpendicular to the downstream end of a bar, layers of sand form great sweeping sets more than 100 feet thick that dip toward the left and right banks. At Walters Ferry, similar layers dip downstream. Such crossbeds could only have formed in very deep water, but they are quite unlike the regular foreset beds of deltas; deltaic deposits typically lie in horizontal courses of limited thickness. Some inclined layers several feet thick at the railroad pit display intricate festoons of laminated sand that demonstrate small-scale cut-and-fill during buildup of the dipping beds (fig. 7).

Although the Melon Gravel is poorly sorted, the largest boulders at particular spots along the canyon are generally uniform in size. Many of them veneer the gravel surface, where they presumably have been concentrated by winnowing during deceleration of flow. They form bouldery fields littered with well-rounded stones ("melon patches") and suggest that the Bonneville Flood was an effective sorting agent in its power to move the largest pieces. (See fig. 8.)

At wide places, or basins, along the canyon, the size and abundance of the boulders decrease abruptly, doubtless because diminishing velocities of spreading floodwater reduced transport capacity. These basins acted as sediment traps and hold most of the Melon Gravel, much of it being heaped in the upper reaches. The Melon Gravel at the downstream ends of basins is dominated by sand, mixed with progressively smaller boulders. The reduction in the size and quantity of boulders is especially evident at the largest basins: Hagerman Valley (mile 151–141); King Hill basin (mile 121–109); and Walters basin (mile 14–0). A similar abrupt decrease in size of boulders transported by Pleistocene floodwater is reported at Portland, Ore., in the broad lowland downstream from the Columbia River Gorge (Trimble, 1963, p. 59–68). Conversely, in canyon constrictions downstream from basins, the size of boulders again increases abruptly.

In brief, few boulders were washed through the basins, and new bouldery debris was picked up by the flood at each canyon constriction. These discontinuities imply that the boulders were all derived locally and that they did not survive more than a few miles of

FIGURE 5.—View upstream of part of the terminus of a gravel bar in Melon Valley, opposite mile 161, showing complex dips of massive layers of bouldery and sandy flood debris. The exposure is 80 feet high.

transport. This inference is confirmed by lithologic identification of boulders at many places along the canyon. A few examples will illustrate the point.

The Snake River now flows over cataracts of silicic volcanic rocks near Twin Falls (mile 185–179) and must have done so at the time of the flood, yet identifiable pieces of these volcanics are extremely rare in Melon Gravel downstream, even short distances below their outcrops. At Melon Valley (mile 161), for instance, fragments of silicic volcanics constitute less than 1 percent of the gravel, and none larger than small pebbles can be found. Apparently, the silicic volcanics were rapidly abraded and pulverized by the flood, although in other stream gravel along the canyon they are one of the most resistant materials.

The largest boulders in Melon Valley (diameters about 4 ft) consist of Thousand Springs Basalt, a distinctive unit of fresh lava that extends a few miles upstream (mile 172) along the northern canyon rim. Debris from weathered rocks (basalt of Glenns Ferry Formation and the Banbury Basalt), which crop out under the rimrock and which extend still farther upstream, survives as boulders of smaller size.

Between Melon Valley and mile 155, outcrops of weathered lava flows (Banbury Basalt) decrease in importance, and the area of Thousand Springs Basalt increases correspondingly. A heap of boulders at mile 155 consists mainly of pieces from the Thousand Springs. Apparently the weathered lava could not survive the few miles of transport. Still farther downstream (mile 150), below other outcrops of Banbury, boulders of weathered basalt again assume importance in the gravel.

Locally derived basalt boulders also occur between Bliss and King Hill. In this reach, as far downstream as mile 130, the river flows in a narrow gorge cut into Banbury Basalt; yet boulders at mile 129 include no large pieces of Banbury. The boulders consist mostly of fresh basalt from rimrock that extends upstream to mile 139 (only along the north rim). The same rimrock supplied practically all the boulders preserved in a great pile of Melon Gravel in the King Hill basin. Cobbles

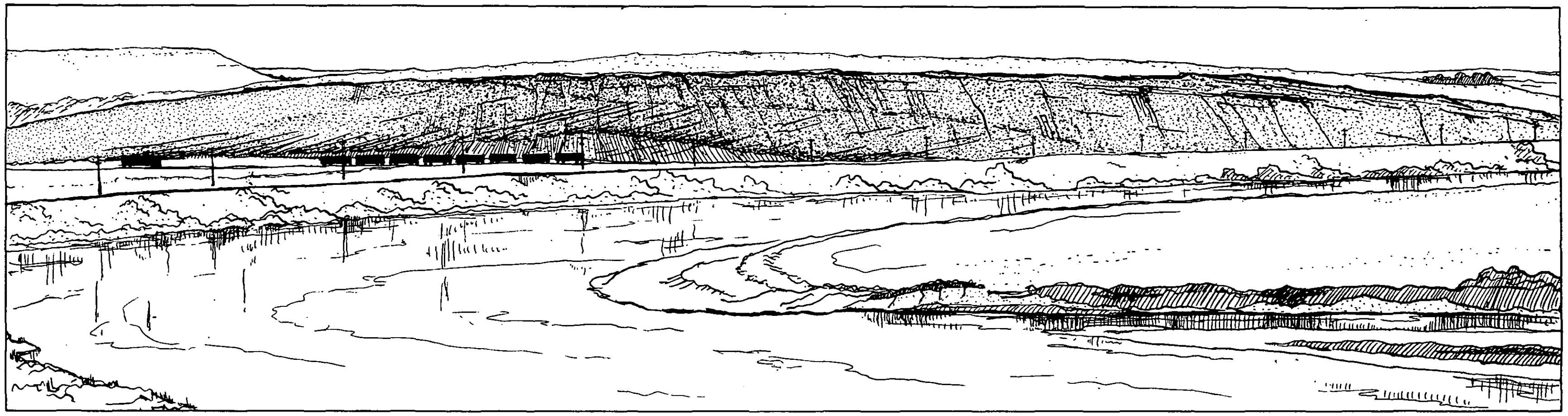


FIGURE 6.—Ballast pit of Union Pacific Railroad in downstream end of sandbar of Melon Gravel at mile 109. The cut extends 1,500 feet from left to right (north to south), is perpendicular to the canyon, and is 125 feet high. It exposes two sets of beds: one set with an apparent north dip of 12° is truncated by another set with an apparent south dip of 5°. (Sketched from a photograph.)

FIGURE 7.—Festoon crossbeds in dipping layers of sand exposed in Union Pacific Railroad pit at mile 109.

of this basalt are identifiable in Melon Gravel as far downstream as Glenns Ferry (mile 107).

The Melon Gravel near Crane Falls, from mile 74 to 64, is entirely from local rocks. The boulders consist of a distinctive brownish-weathered lava (basalt of Bruneau Formation) that forms the canyon at this place, and, because a basin devoid of gravel extends some distance upstream, the finer constituents in flood debris at Crane Falls are also of local origin. The Melon Gravel at Walters similarly was derived solely from a constricted segment of canyon just upstream, mile 14–30.

PHYSIOGRAPHY

The Melon Gravel forms gigantic bars and enormous heaps of bouldery detritus at places along the Snake River canyon where the flood velocity was retarded, especially at the upper ends of local basins. Although

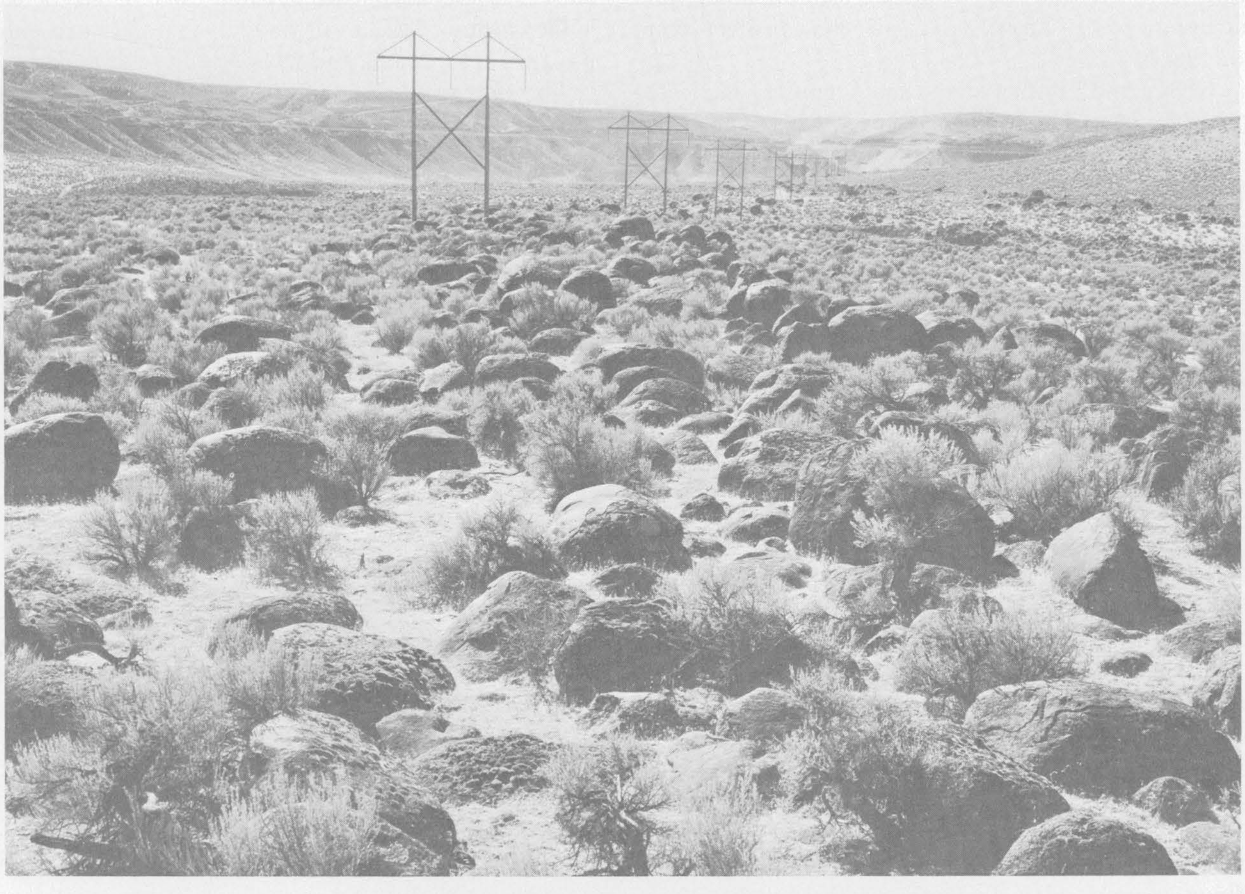


FIGURE 8.—Boulder train on surface of Melon Gravel 100 feet above Snake River 3 miles downstream from Bliss Dam, Idaho. Boulders in the foreground are from 3 to 5 feet in diameter, and some in the distance are as large as 10 feet. Exposed surfaces of the boulders have been polished by the action of windblown sand. Weathered rinds about half an inch thick on some boulders are now exfoliating.

the canyon at the time of the flood had its present depth and its major outlines, such deposits made numerous physiographic changes. The gravel filled the canyon in places to a depth of 300 feet, greatly reducing the former width and blocking the mouths of some tributary valleys. Furthermore, huge bars built in midcanyon determined the trend of deep marginal channels perched between the bars and the canyon walls.

The bars of Melon Gravel resemble grossly magnified versions of ordinary bars found along braided streams. They have a streamlined form, which is tapered at both ends, and they trend downstream. In places, two or more gigantic bars lie close together, although not necessarily at equal height, and demonstrate by their parallel trends that they were built simultaneously. The bars generally lie along the axis of the canyon, where they stand isolated from the walls, but a few are along the inner sides of canyon bends. Some bars are tied to knobs of resistant bedrock that rise from the canyon floor, and others hang loosely from buttresses that project from canyon walls.

The bars are of impressive size. A typical bar is 1–1½ miles long and about half a mile broad, measured with respect to the lowest closed contour. The highest place along a bar, commonly from 50 to 150 feet above surrounding gravel, generally is near the middle. The fore and aft slopes on bars range from 1:100 (Melon Valley, mile 160) to about 5:100 (Weatherby Springs, mile 71), and the side slopes are considerably steeper.

The streamlined shapes of the bars—looking like magnified channel deposits of modern streams—suggest that they have been preserved in virtually original form; that is, they are constructional shapes left during subsidence of the Bonneville Flood and have been scarcely modified by later erosion. Because of their streamlined form, discontinuous distribution, and lack of pairing with companion surfaces, the bars have no resemblance to terraces built by aggrading rivers; they surely represent bedload material deposited in deep water. The highest bars demonstrate that floodwater was at least 300 feet deep in some places (table 1), but even these bars indicate only a minimum height of floodwater at peak discharge. Like the lower bars, they have surfaces strewn with boulders that suggest winnowing during retarded flow as floodwater subsided.

Outlets of some small tributary valleys, obstructed by Melon Gravel, also demonstrate the height of the flood. One of the obstructed tributaries is spring-fed Billingsley Creek, which joins the Snake River at mile 142 after passing through a narrow orifice 200 feet higher between a bar of Melon Gravel and the canyon wall. Within the obstructed part, Billingsley Creek pursues a winding meandering course in a swampy alluvial plain (fig. 19). Jolley Flat, a nearly level alluvial plain 200 feet above the Snake River 3½ miles southeast of King Hill, is another tributary valley blocked by Melon Gravel. Dumping of gravel at the valley mouth caused the spread of alluvium (fig. 20).

MARGINAL CHANNELS

The path of the Bonneville Flood from Melon Valley downstream is marked by numerous abandoned channels next to the canyon walls. These marginal channels are a direct consequence of gravel dumped in midstream, which detoured floodwater into troughs beside gravel bars. Most channels are bounded by bars of Melon Gravel on one side and by canyon walls on the other, although a few abandoned channels lie wholly within gravel. Some channels are several miles long and as much as 150 feet deep with respect to adjacent bars of gravel. The principal channels are shown in figure 2, and their major dimensions are listed in table 1. Topographic details of several channels are shown in figures 16, 19, 20, 22, and 23.

The marginal channels are perched high above the Snake River and do not now carry water, although small ponds fed by springs and irrigation water occur in irregular depressions 25–50 feet deep along channel floors. Beside these channels the Snake River follows a deep trough that probably existed during the flood—a physiographic relation that implies gross discontinuities along the canyon floor. Even these irregularities were deeply submerged by the flood. The threshold of a marginal channel at Pasadena Valley, for instance, 170 feet above the canyon floor, was covered with water at least 120 feet deep at peak discharge, as shown by the height of an adjoining gravel bar.

IMPOUNDED WATER

If the highest rise of floodwater is estimated from the height of Melon Gravel and from a few unmistakable erosion features along the canyon, the resultant profile shows that floodwater was partly impounded at canyon constrictions and that basins upstream held temporary lakes (figs. 2, 3). That is, the constrictions acted briefly as hydraulic dams. The principal lakes and their effect on deposition of flood debris are described in a later section of this report, but a brief summary of their geography is pertinent to the discussion that follows. Below the canyon constriction near Swan Falls (mile 26), the canyon progressively widens, and no lakes were formed. Above Swan Falls, however, extending 35 miles to the mouth of the Bruneau River and thence into the lower Bruneau valley, there was a large lake. Still farther upstream, above a constriction at mile 75, a series of lakes extended past King

TABLE 1.—*Topographic relations of marginal channels*

Locality	Length of channel (miles)	Altitude difference between channel floor and adjoining gravel bar (feet)	Minimum height of channel floor above present Snake River (feet)	Maximum height of gravel bar above present Snake River (feet)	Location of measurement			Topographic quadrangle map that shows channel [1]
					Sec.	T.	R.	
Melon Valley	2.6	80	80	160	11–12	9 S.	14 E.	Thousand Springs.
Salmon Falls Creek	2.7	120	20	140	30	8 S.	14 E.	Do.
Hagerman Valley	4.0 (Hagerman Valley and Hagerman townsite)	35	140	175	25, 26, 35, 36	7 S.	13 E.	Hagerman.
Hagerman townsite		115	100	215	14	7 S.	13 E.	Do.
Pasadena Valley	5.7 (Pasadena Valley and Frog Hollow)	150	140	290	31, 32	5 S.	11 E.	Pasadena Valley.
Frog Hollow		130	125	255	19	5 S.	11 E.	Do.
Jolley Flat	6.5 (Jolley Flat and King Hill)	110	145	255	16, 21	5 S.	11 E.	Do.
King Hill		100	160	260	6	5 S.	11 E.	King Hill (15 min).
Glenns Ferry	3.0	50	40	90	31	5 S.	10 E.	Glenns Ferry.
Indian Cove	3.0	70	25	95	1, 2	6 S.	7 E.	Indian Cove.
Opposite Rattlesnake Creek.[2]	1.6	50	235	[3] 285	25, 26	5 S.	5 E.	Bruneau.
"Bruneau cutoff"	7.0	[4] 30	[5] 270	[4] 260	36	5 S.	4 E.	Bruneau (15 min).
					31–36	5 S.	5 E.	
Weatherby Springs	1.7	140	100	240	16, 21	5 S.	5 E.	Bruneau.
C. J. Strike Dam	2.0	75	60	135	28, 33	5 S.	4 E.	Do.
Walters Ferry	4.5	80	130	210	15, 22	1 S.	2 W.	Walters Butte.

[1] All quadrangles are 7½ min, except where otherwise designated.
[2] Upland channel.
[3] Highest reach of eroded bedrock knobs.
[4] Height of boulder gravel at downstream end of channel.
[5] Ranges from 2,711 ft alt at upper end to 2,600 ft at lower end.

Hill to mile 121, each successive lake being at slightly higher level because of connecting canyon necks. The basin at King Hill held a considerable body of water and trapped most of the debris flushed from the steep canyon upstream. This accounts for a paucity of Melon Gravel in the lower basins. The comparatively low velocities at constrictions connecting the chain of lakes between King Hill and mile 75 may explain an apparent lack of erosion at these narrow places. Floodwater, however, moved more or less rapidly through each of these lakes, and they must be regarded as dynamic features along the flood path.

Fine-textured surficial deposits preserved in backwater areas suggest that water impounded in the lakes was roily with suspended sediment, which settled out where currents were weak. (Suspended material near the center of a basin probably was flushed downstream by faster currents.) Such backwater deposits are sparse and isolated, and their identification must be hedged with doubts. During detailed mapping near King Hill, however, which was one of the most likely places for entrapment of suspended load, three outcrops were located that may represent backwater deposits left by the Bonneville Flood.

One possible backwater deposit rests on terrace gravel (Crowsnest Gravel) in the NW¼ sec. 9, about 2 miles east of King Hill. (See fig. 20.) The deposit is 20 feet thick, and the top is at an altitude of 2,760 feet, the same as the height of flat-topped remnants of Melon Gravel in the center of the basin. This level probably was determined by a temporary stillstand controlled by a canyon constriction at mile 100. The deposit is a massive mixture of silt, some clay, and granitic sand such as is found in nearby bedrock (Glenns Ferry Formation). The deposit is probably not colluvium because it lies on a flat terrace half a mile from bedrock slopes. It is plausibly accounted for as a backwater deposit, perhaps mixed with material supplied by Clover Creek, a tributary that joins the Snake River at this place.

A second possible backwater deposit is near the center of sec. 26, about 2½ miles west of Glenns Ferry in the shelter of a basalt-capped spur along the canyon wall. The deposit rests on Crowsnest Gravel and on a sloping wall cut into the Glenns Ferry Formation. It rises on the slope to an altitude of from 2,750 to 2,775 feet, about the same as that of the deposit already mentioned. This second deposit is as thick as 50 feet and consists of inclined beds, concordant with the slope and composed mainly of silt, but including some pebbles and fragments of basalt that crop out on the slope above. The dominance of fine-grained material, the bedding, and the abrupt termination upslope suggest that this is a backwater deposit containing debris that lay on the slope at the time of the flood.

A third possible area of backwater deposits is on the opposite side of the valley, 2½ miles southwest of Glenns Ferry. The deposits are exposed in several shallow gullies graded to a terrace of Crowsnest Gravel. They are about 25 feet thick and pinch out rapidly upslope at an altitude commensurate with the highest stand of floodwater, a little below 2,800 feet. These deposits are dominated by massive light-colored fine-grained material of the kind that forms the canyon in this area, but they probably do not represent colluvium. Nearby slopes in analogous topographic situations, but above the flood height, have no such deposits. Thus these fine-grained materials could be some of the suspended load transported by the flood.

Backwater deposits have not been found in the basins downstream, but they would be difficult to identify in these places owing to extensive badlands.

SCABLAND

The term "scabland" was introduced by Bretz in 1923 (see review by Bretz and others, 1956; Bretz, 1959) for chaotically eroded basalt areas in eastern Washington from which a thick mantle of loessial soil was swept by passage of glacial floods. The term has since become familiar in the vocabulary of geology. Bretz emphasized such incredible erosional features of scabland as colossal anastomosing channels, gigantic coulees, dry falls, and empty rock basins, which together make a weird landscape unlike any other then known on earth. Features of this kind are also found at places along the path of the Bonneville Flood through the Snake River Plain, particularly at Twin Falls, although at reduced scale.

At most places in the Snake River Plain, the most obvious sign of scabland erosion is a lack of surficial sediment that is still preserved on the higher parts of a lava flow. The extent of the Bonneville Flood on uplands can be judged from the geographic distribution of such barren tracts. Moreover, even where major scabland features are lacking, surfaces of lava flows washed by the flood display numerous minor erosional features that indicate a former forceful flow of water. Smoothed, polished, and fluted surfaces have formed by corrasion of rushing sand (fig. 9), and the upper parts of lava flows have been stripped and washed away, presumably by the plucking of lava blocks. Close inspection of scoured lava surfaces shows blunted edges on exposed vesicles and enlargement of pore spaces ordinarily crowded with fragile crystals. Removal of blocks from lava flows is indicated by absence of vesicular upper layers with ropy skins and by the consequent exposure of columnar lava that cooled deeper within flows. Comparison with uneroded lava, or with nearby remnants in the scabland, allows an estimate of the depth of stripping—commonly several feet. These processes of corrasion and stripping formed an intricately dissected lava surface of branching channels, dry falls, and rock basins, which are small-scale replicas of the gigantic features emblematic of scabland.

Large erosion features of scabland that imitate the weird forms made famous by Bretz will be described in appropriate places in the discussion that follows.

A

B

FIGURE 9.—Minor erosion features in basalt scabland formed by the Bonneville Flood.

A. Upstream end of small sluiceway on basalt 4 miles southeast of King Hill and 175 feet above present Snake River. Corrasion has formed rounded polished surfaces marked by minute fluting that indicates the direction of turbulent flow. Sections through exposed vesicles have blunted edges, and pore spaces ordinarily occupied by fragile crystals have been gutted and enlarged. Blocks of lava that formerly filled the sluiceway were plucked out and washed downstream.

B. Uneroded part of the same basalt flow as shown in *A* but 2,000 feet southeast and 75 feet higher. This outcrop was covered by the flood but lay in a backwater protected from rapidly moving debris. Accordingly, the basalt exhibits no corrasion or plucking. The scant soil cover is characteristic of this lava flow—but not generally of others in the path of the flood—and does not indicate scabland. The accumulation of soil dates from a time before the flood.

PATH OF FLOOD ABOVE TWIN FALLS

UPPER SNAKE RIVER PLAIN

The route of the Bonneville Flood to the Snake River Plain and westward along the Snake River was largely controlled by topography that exists today (fig. 1). From Red Rock Pass, floodwater flowed north down the valley of Marsh Creek into the lower Portneuf River canyon and onward to the Snake River Plain at Pocatello. Here, at the canyon mouth, the flood met slack water of a temporary lake that was held by a resistant lava barrier—the Cedar Butte Basalt at an altitude of 4,450 feet near American Falls, 30 miles downstream—and bouldery debris 50–80 feet thick known as Michaud Gravel was dumped on the lake bottom. The largest pieces that were carried into the lake range from 8-foot boulders at Pocatello to cobbles at a distance of some 10 miles (fig. 10). Discharge from the lake was by two principal routes over and around the lava barrier, so that channels and cataracts were cut on the uplands and along the canyon wall of the Snake River (Trimble and Carr, 1961b, fig. 2). The largest of these was Lake Channel, an upland spillway that rejoined floodwater along the Snake River at an altitude of 4,280 feet, 10 miles below the lava barrier (fig. 10). Gravel bars containing 20-foot boulders of local basalt were built across the mouths of some spillways.

In the next 30 miles downstream, the flood followed a broad valley carved out by the Snake River and left no obvious sign of its passage, before spreading widely over a flat alluvial plain that surrounds Rupert. This plain is only a few feet above present river level and must have been inundated throughout most of the Bonneville Flood, although tangible effects of the volu-

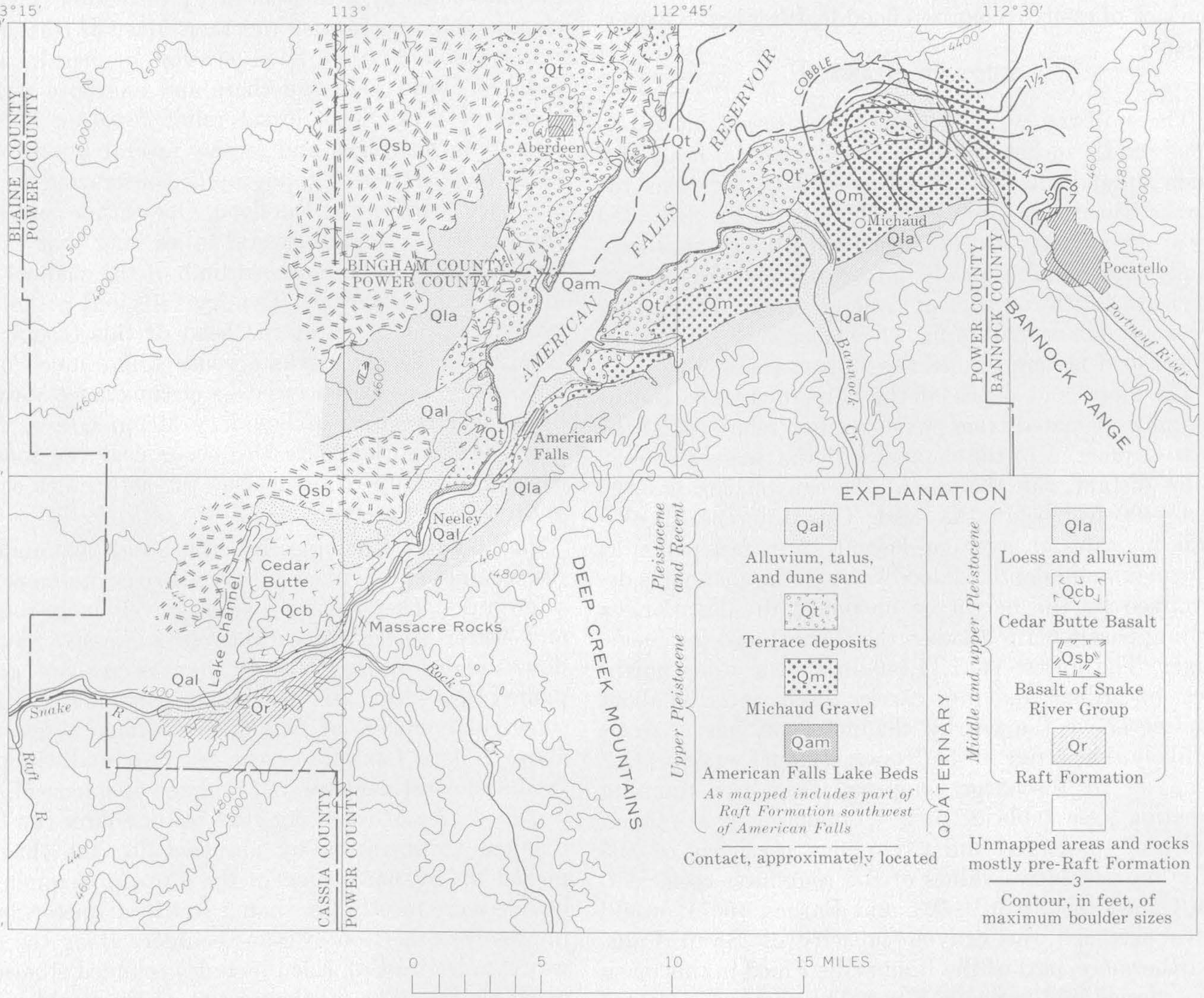


FIGURE 10.—Geologic sketch map of American Falls area (slightly modified from Trimble and Carr, 1961b, pl. 1). Contours of boulder sizes at Pocatello added from Trimble and Carr (1961a, fig. 69.2). For area of map, see figure 1.

minous discharge are hard to find. Between Rupert and the present Snake River, a subdued relief expressed by discontinuous west-trending swales 5–10 feet deep, several miles long, and as much as a mile wide presumably was produced by passage of the flood. Stearns (1962) suggested that fossil mammals in gravel 6 miles northeast of Rupert may have been drowned by the flood, but the gravel has not been shown to be a deposit of the flood.

A spillway 13 miles west of Rupert at an altitude of about 4,200 feet, which probably was covered with water at least 30 feet deep (as indicated by the height of erosional features), suggests that floodwater in the Rupert basin rose to an altitude of about 4,230 feet and flooded an area of 300 square miles to a depth of as great as 80 feet. The average depth of impounded floodwater would have been about 50 feet. Tranquil flow through such a broad lake could be the explanation for the lack of easily recognized flood features in the Rupert basin.

RUPERT CHANNEL

The spillway west of Rupert is a broad inconspicuous saddle in basaltic lava and lies at the head of a wide upland channel 30 miles long that rejoins the Snake River near Twin Falls. The channel is delimited by an eroded tract of basalt scrubbed clean of soil (scabland) and scoured locally into small rock basins and dryfalls. Scattered bars of boulder gravel occur along the route (inset map in fig. 1). This arm of the Bonneville Flood is here termed the Rupert channel.

The slope and depth of the Rupert channel can be roughly estimated from physiographic relations. At the nearest junction of the channel with the Snake River, 22 miles distant, the altitude of the canyon rim is 3,800 feet—400 feet below the head. This difference in altitude indicates an average descent of 18 feet per mile. The maximum depth of floodwater in the channel is determined by the height of unspoiled divides along a rolling basalt plain between the channel and the Snake River. The lowest pass (4,140 ft alt), a swale northwest of Milner that now carries ditch water, is about 70 feet above the nearby channel floor, but it seems unlikely that water in the Rupert channel was ever this deep. If so, discharge computed from the Manning equation (see table 2, p. 25), assuming a minimum width of 10,000 feet and a roughness coefficient of 0.05 (for representative values of the roughness coefficient, see Chow, 1959, p. 104–123, and Barnes, 1967), would have exceeded the canyon capacity at Swan Falls. Furthermore, part of the Bonneville Flood in this reach was carried by the Snake River. The probable depth of water in the channel may be estimated better by tracing the flood profile from unmistakable signs of catastrophic erosion that apparently mark the highest rise of floodwater. In this way, for the relatively narrow upper part of the channel, floodwater appears to have been locally at least 50 feet deep, but the average depth must have been considerably less—perhaps less than 20 feet. The true depth at peak discharge cannot be measured accurately, even from detailed knowledge of the flood profile, because of indeterminate erosion that undoubtedly took place during subsidence of floodwater.

Topography within the Rupert channel, as typifies scabland, is extraordinarily irregular. The maximum local relief is at a group of dry falls and giant potholes between Eden and Wilson Lake Reservoir, which range in depth from 50 to 120 feet (fig. 11); but at many other places along the channel, abrupt changes in altitude amount to several tens of feet. In addition, innumerable lesser knobs and pits are displayed on topographic maps by a random array of deviously shaped closed contours crowded together. Most of this chaotic relief resulted from flood erosion of basalt, which plucked blocks here and there and unevenly stripped sheets of lava. Some broad relief features, however, appearing as ridges and swales several hundred feet long, may represent topography constructed by lava and then modified by the flood. One rather continuous swale forms a trough several miles long that extends westward along the southern limb of the channel from Wilson Lake Reservoir. The dry falls and potholes already mentioned are at the head of this trough. The trough apparently marks a route where much of the floodwater was concentrated—a circumstance borne out by some large bars of bouldery Melon Gravel found here. Scattered boulders also occur near the southern edge of the Rupert channel as far as 5 miles east of Wilson Lake Reservoir.

The boulders lithologically match basalt that underlies the channel and evidently have traveled no more than a few miles. They assume a progressively more rounded and better sorted appearance in successive deposits downstream, although these changes are not accompanied by a systematic decrease in particle size. Blocky subangular chunks of basalt are common a few miles above Wilson Lake Reservoir, but nearly all the pieces farther downstream are well rounded or spherical. Such a high degree of rounding close to the source can be attributed to corrasion by abrasive detritus that was picked up by floodwater in the Rupert channel. The boulders are mostly less than 5 feet in diameter, but an impressive collection of giant boulders along the highway 3 miles west of Eden includes rounded stones that reach 10 feet. The maximum size of the boulders may have been determined not so much by the transport power of the flood as by the spacing of cracks in the

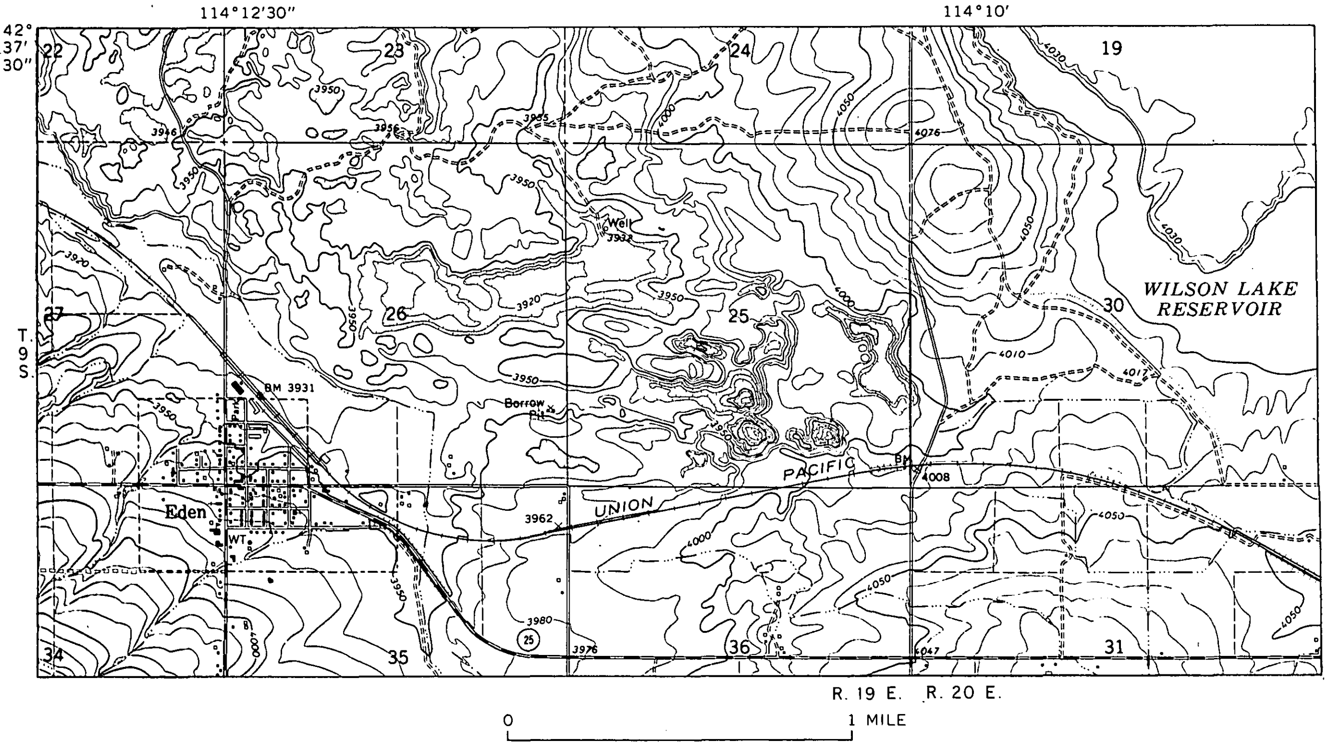


FIGURE 11.—Dry falls and giant potholes near Eden, Idaho, along south margin of Rupert channel. Typical scabland topography lies north of the railroad, but water of the Bonneville Flood covered the present site of Eden (3,960 ft alt) and also covered Melon Gravel at the 4,020-foot altitude between the potholes and Wilson Lake Reservoir. Thus the local flood gradient was about 24 feet per mile, and floodwater in the area of the potholes was about 30 feet deep. (From U.S. Geol. Survey topographic map of Eden quadrangle, Idaho, scale 1: 24,000.)

basalt. The lack of sorting of boulders suggests that basalt pieces were picked up locally at various places along the channel.

MILNER REACH

From Milner (mile 207) to the junction with the Rupert channel (mile 186), the Snake River follows a narrow basalt canyon with relatively smooth, straight walls. Floodwater was released from the Rupert basin via this canyon, as well as by simultaneous spill into the Rupert channel. This canyon segment—here called the Milner reach—appears to have formed initially by recession of falls along a course determined by the south margin of basalt of the Snake River Group (see map by Malde and others, 1963) and was then modified by the Bonneville Flood. Stearns (1962), however, inferred that this narrow canyon was cut later than the flood by seasonal glacial meltwater augmented by occasional overflow from Lake Bonneville. Although the actual sequence of events cannot be determined from stratigraphic evidence, the history of the Milner reach can be appraised from physiography and from the capacity of the reach to transport floodwater, as are discussed below. I conclude that this gorge largely antedates the Bonneville Flood but that it was noticeably enlarged by flood erosion, particularly at the downstream end. Erosion since the flood appears to have been comparatively minor.

Floodwater was delivered to the Milner reach from the Rupert basin through a gap less than a mile wide about 4 miles upstream. From this gap the flood descended rapidly to an altitude of 4,160 feet at Milner and formed a belt of scabland 1½ miles broad at the canyon head.

In the stretch downstream to Murtaugh (mile 198) the canyon is rather narrow (about 600 ft) and comparatively shallow (200 ft or less). This segment is bordered by continuous scabland, altogether a mile across, the existence of which indicates that the carrying capacity of the canyon was at one time exceeded by the flood. Boulders of flood debris below rapids in the canyon at Murtaugh form a pile 100 feet thick. At this steep place (gradient 35 ft per mile), the Snake River has cut a narrow trough 50 feet below the base of the gravel; this depth gives a measure of erosion since the flood.

In the next 12 miles below Murtaugh—that is, downstream to the junction with the Rupert channel—the canyon is remarkably uniform in width and depth, about 1,100 by 325 feet, with smooth vertical walls and a boxlike cross section. The canyon floor descends steadily at a gradient of about 24 feet per mile. The canyon walls are nearly devoid of talus, and practically no detritus occurs along the floor (fig. 12); apparently the canyon was flushed clean by passage of the Bonneville Flood. Because the floor is wider and less steep than at Murtaugh (where downcutting below flood debris amounts to only 50 ft), erosion along this segment since the flood must have been slow. That is, the present aspect of the canyon below Murtaugh is largely a relic of the Bonneville Flood. But is this segment of canyon also a relic of a still earlier time? The distribution of scabland along the canyon rim provides an answer. Scabland along this part of the Milner reach occurs only from Hansen Bridge (mile 189) downstream, and its general absence from Murtaugh to Hansen Bridge demonstrates that most of the canyon below Murtaugh was capable of carrying all floodwater delivered from the Rupert basin. This canyon segment is therefore more ancient than the flood. Only the lower part of the canyon was overtopped by floodwater, and at mile 187 rounded basalt boulders as large as 6 feet in diameter form a low bar on the south rim, 350 feet above the Snake River (fig. 14). The rather peculiar circumstance of scabland along the lower part of the Milner reach is discussed below.

The degree to which the Milner reach may have been enlarged by the Bonneville Flood can be surmised from the carrying capacity at Hansen Bridge (mile 189, fig. 13 section *J–J′*), a narrow place where floodwater overflowed the canyon rim. The Manning equation indicates that the present capacity at brimful stage through this constriction would be 19 million cfs (table 2). The capacity below Hansen Bridge, where the canyon is wider (fig. 14), would be correspondingly greater. Because a probable discharge of 15 million cfs is computed at Swan Falls (p. 12) and because a large amount of floodwater was carried simultaneously by the Rupert

FIGURE 12.—View of Snake River canyon upstream from Hansen Bridge (mile 189), showing the near absence of talus and a lack of stream debris along the canyon floor. At this place the canyon is 320 feet deep and only 600 feet wide. A thin layer of basalt was stripped from the rim on both sides of the canyon, and this left scabland areas which indicate that the canyon was at one time brimful.

TABLE 2.—*Discharge capacity of Snake River canyon at selected constrictions, as computed from the Manning equation:*

$$Q=\frac{1.49}{n}AR^{2/3}S^{1/2}$$

[*Q*, discharge (cubic feet per second) at maximum high water, assuming roughness coeficient (*n*) of 0.03; *A*, area of cross section of water at highest flood level and at present canyon depth and width; *R*, hydraulic radius (area divided by wetted perimeter); *S*, slope ratio; for example, 12 ft per mile equals a slope ratio of 0.00227]

Section	*A*	*R*	*S*	*Q*
A–A′ (Swan Falls)	405, 000	215	-------	[1] 15×10⁶
B–B′ (Crane Falls)	198, 000	149	0. 00246	[2] 13. 7×10⁶
C–C′ (Barber Cabin)	456, 000	215	[3]. 00227	38. 8×10⁶
D–D′ (Indian Cove)	676, 000	242	[3]. 00227	62. 2×10⁶
E–E′ (The Narrows)	651, 000	240	[3]. 00227	59. 4×10⁶
F–F′ (Thousands Springs)	411, 600	191	. 00227	32. 2×10⁶
	29, 400	49	. 00227	. 9×10⁶
H–H′ (Ellisons Springs)	487, 000	268	. 0038	61. 5×10⁶
I–I′ (Blue Lakes)	1, 346, 000	378	. 0038	214×10⁶
J–J′ (Hansen Bridge)	162, 000	156	. 0062	19. 1×10⁶

[1] Critical-depth calculation. (See p. 12.)
[2] Section overtopped by flood.
[3] Assumed.

channel, the discharge at Hansen Bridge must have been much less than 19 million cfs, notwithstanding possible downstream attenuation of the flood. It follows that the canyon during peak discharge, when scabland formed along the rim, must have been smaller than now and that the present augmented size resulted from flood erosion. If we assume that the Milner reach carried half the total discharge (the other half being carried by the Rupert channel), the canyon at Hansen Bridge could have been doubled in size by passage of the flood. The part below Hansen Bridge, which is twice as wide but which was nonetheless overtopped by floodwater, may have increased in size four times.

The foregoing argument depends on the significance ascribed to scabland along the canyon rim and ignores the possible effect of the confluence of the Rupert channel 3 miles downstream from Hansen Bridge. As will be explained shortly, the flood at this junction rose above the canyon. Although the flood height at the junction was 120 feet below scabland at Hansen Bridge (a flood gradient of 40 feet per mile), it may have created some backwater in the canyon. If so, discharge calculated from the Manning equation would be misleading, because of impaired flow, and conclusions about canyon dimensions inferred from discharge would be inaccurate. These gigantic features of the flood overwhelm the imagination but it seems unlikely that backwater in a gradient of 40 feet per mile would have greatly reduced the flood velocity, and I therefore believe that considerable erosion took place in the downstream end of the Milner reach. In fact, the calculated discharge at Hansen Bridge, and hence the inferred increase in canyon size by flood erosion, is based on a flood gradient of only 33 feet per mile, which is the local gradient of the canyon floor. Nonetheless, backwater is the only plausible explanation for the rise of floodwater above the canyon rim downstream from Hansen Bridge and for the consequent erosion of marginal scabland. Forceful flow along this segment, despite the effect of backwater, is demonstrated by the 6-foot boulders already mentioned on the canyon rim at mile 186.

EROSION NEAR TWIN FALLS

The most impressive erosion features produced by the Bonneville Flood are along the Snake River canyon near Twin Falls (mile 186–175), where the Rupert channel joins the Milner reach (fig. 14). This stretch of canyon is nearly 500 feet deep and ranges from 1,300 feet to a mile in width (fig. 13, section *I–I′*). This exceeds the size of the canyon immediately above and below. The north rim, where floodwater entered from the Rupert channel, is embayed by several large alcoves (dry falls), and the south rim from mile 186 to 180, where water spilled from the Milner reach, displays a ragged edge. The effect of spillover along the north and south rims apparently was to broaden the canyon to a width considerably more than its original size.

These erosional features indicate that this stretch of canyon was virtually brimful at peak discharge. The inferred flood profile (fig. 3) would have been below the canyon rim only from mile 180 downstream, where scabland is absent along the south side. But even here, projection of the profile suggests that floodwater was not far below the canyon edge. If this inference is correct, erosion along the north and south rims was not accomplished by water spilling as cascades in the ordinary sense, but was done by extraordinary turbulence in rapidly moving deep water. (See discussion of "kolk-action" in Bretz and others, 1956, p. 1028–1029.) This conclusion has significance for understanding other erosional features along the canyon floor.

Through this broad canyon the Snake River descends over massive and resistant outcrops of silicic volcanic rocks (mile 185–179), which make up the lower story of the canyon. These outcrops form cataracts at Pillar Falls and Shoshone Falls and represent impediments to canyon entrenchment. Pillar Falls, although having a lip only 20 feet high, is surrounded by crags of scabland that reach 175 feet above the river. Shoshone Falls, 210 feet high, is bordered by scabland that extends 80 feet higher. The Twin Falls plunge 150 feet from basalt half a mile upstream from another outcrop of silicic volcanics. Between mile 180 and 179 an outcrop of silicic volcanics forms a jagged mass of scabland that rises 200 feet above the canyon floor (fig. 15).

These gigantic erosional features along the canyon floor probably represent mainly the effect of turbulence in phenomenally deep water, although they must have

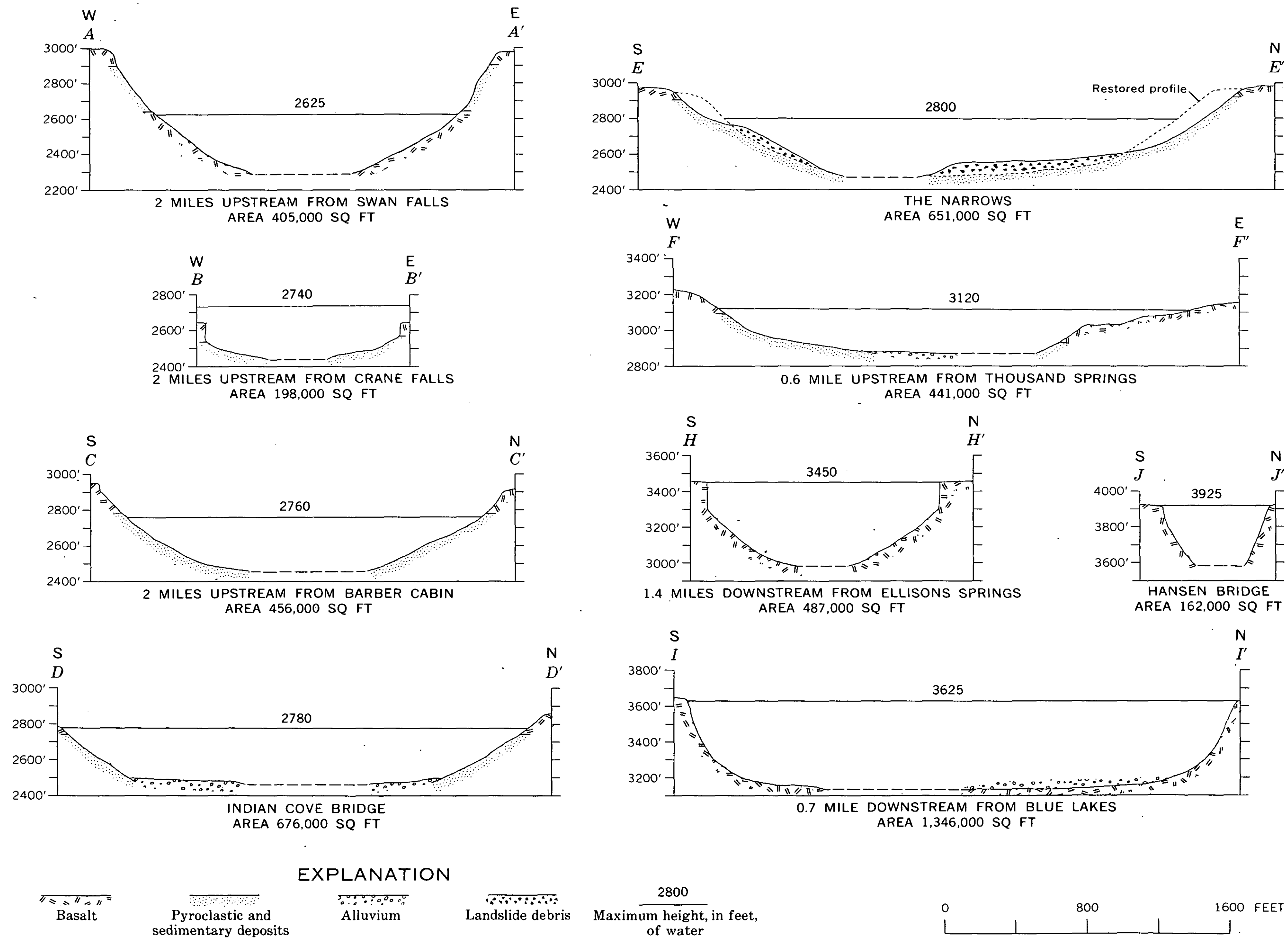


FIGURE 13.—Sections of Snake River canyon at principal constrictions, showing maximum height of Bonneville Flood. Section *G–G′* shown in figure 17.

made a series of rapids and cataracts as the flood waned in volume. Pillar Falls and Shoshone Falls coincide in a curious way with abrupt embayments on both sides of the canyon, which probably were eroded concurrently by turbulent floodwater when the canyon was full. Whatever the mechanics of origin, catastrophic erosion of these silicic volcanics undoubtedly deepened the canyon. Because the present cataracts descend from bordering scabland, rather than from a lip upstream from scabland, they apparently mark the approximate limit of recessional erosion during the flood. That is, the topography suggests that recession of the falls since the flood has been comparatively negligible and that the present shape of the canyon floor is largely a relic of the Bonneville Flood. This conclusion is startling, especially in view of the 30,000-year age assigned to the flood, but I can interpret the present canyon near Twin Falls in no other way and only as impressive evidence of the magnitude of the Bonneville Flood.

The alcoves along the north canyon rim, which represent places of especially turbulent flow from the Rupert channel, define a spillway 10 miles wide. The largest are known as Blue Lakes alcove, Devils Corral, and Devils Washbowl. In describing the alcoves, Russell (1902, p. 127–130) noted several peculiar physiographic features: absence of entering streams; headward enlargement into amphitheaters; and a general lack of talus, particularly at the semicircular heads of alcoves. Observing also that springs emerge at several alcoves, he attributed the alcoves to spring action. This hypothesis was elaborated by Stearns (1936, p. 444–447), who concluded that the alcoves were formed mainly by slow solution of basalt by spring water—a process that supposedly accounted for the perplexing lack of talus and for the headward enlargement of alcoves. He (Stearns and others, 1938, p. 89) identified boulders at the mouths of alcoves as coarse alluvium left in the wake of the receding springs.

The physiographic features that puzzled Russell and Stearns have long been recognized as typical of dry falls formed by glacial floods in the scabland of eastern Washington (Bretz, 1959; and many previous reports by Bretz dating from 1923). Plunge pools below such falls are flushed clean of debris by the force of turbulent water, and the falls characteristically erode into a semicircular form. In current understanding, the dry falls of eastern Washington were probably completely submerged by floodwater, which moved in giant eddies—"subfluvial tornados" (Bretz and others, 1956, p. 1028)—and eroded mainly by cavitation rather than solely by cascading over an edge. This mechanism probably prevailed here, as well, at least for Devils Corral and Devils Washbowl, although the flood profile may have been slightly below the lip of Blue Lakes alcove. The alcoves also display various other physiographic features not explained by the spring hypothesis, but readily understood as consequences of flood erosion.

Tiered or staircased sets of abandoned plunge pools are common in alcoves that have been carved from layers of basalt. The basalt layers are from 25 to 50 feet thick. Erosion of these layers by turbulent water produced a random series of basins at various levels not connected by through drainage. Such basins are especially well displayed at Devils Washbowl and Devils Corral. Some of the basins are filled with spring water, but most of them are dry.

The head of Blue Lakes alcove, a steep-walled amphitheatre 300 feet deep and 1,500 feet wide, is cut in a single massive basalt flow (filling a former canyon of the Snake River) and exhibits no tiers of plunge pools. Stratified basalt flows toward the mouth of the alcove, however, as shown in a photograph by Russell (1902, pl. 24), were partly stripped so as to form benches, which are further diversified by small basins. (See also fig. 14.) Such stripping is a common feature along the north edge of the canyon and evidently was caused by water spilling from the Rupert channel.

Each major alcove is actually a group of dry falls that join a common stem. The plan of Devils Corral, for instance, resembles a misshapen glove, with several tributary alcoves and with plunge pools at various levels. The west branch of Blue Lakes alcove, perched 220 feet above the main stem, is cut off by a nearly vertical wall. The maze of minor alcoves between Devils Corral and Devils Washbowl, however, is so chaotic that it lacks a noticeable pattern.

Scattered boulders are found on some benches within the alcoves and cannot be explained by the spring hypothesis. (See Russell, 1902, pl. 24.) The boulders are rather angular, but the edges and corners are blunted. Some are more than 10 feet in diameter. They sit isolated on barren basalt devoid of any other kind of gravel. Their transport, even for short distances, would require great force.

The ragged canyon rim on the south side, where water spilled from the Milner reach (mile 186–180), is diversified by two waterless side canyons that form short gashlike alcoves at mile 185. These are minor topographic features compared to the alcoves on the north side but are worthy of emphasis because they suggest the power of the flood. The larger alcove, the east, is 3,000 feet long, 300 feet wide, and about 100 feet deep. Both have scalloped east rims. The alcoves contain no debris except for some windblown sand and scattered

FIGURE 14.—Topographic map of Snake River canyon near Twin Falls, Idaho, showing erosion features produced by the Bonneville Flood. The limit of floodwater on the upland is determined by the extent of scabland, which is expressed on the map by numerous irregular contours and by closed basins and knobs. Gravel pits in scabland north of the canyon are in scattered patches of Melon Gravel. The impressive erosion features along the canyon and on the canyon floor are described in the text. Circled numbers indicate river mileage measured upstream from Hot Springs Ferry. Section *I–I′* is shown in figure 13. (From U.S. Geol. Survey topographic maps of Twin Falls and Kimberly quadrangles, Idaho, scale 1 : 24,000.)

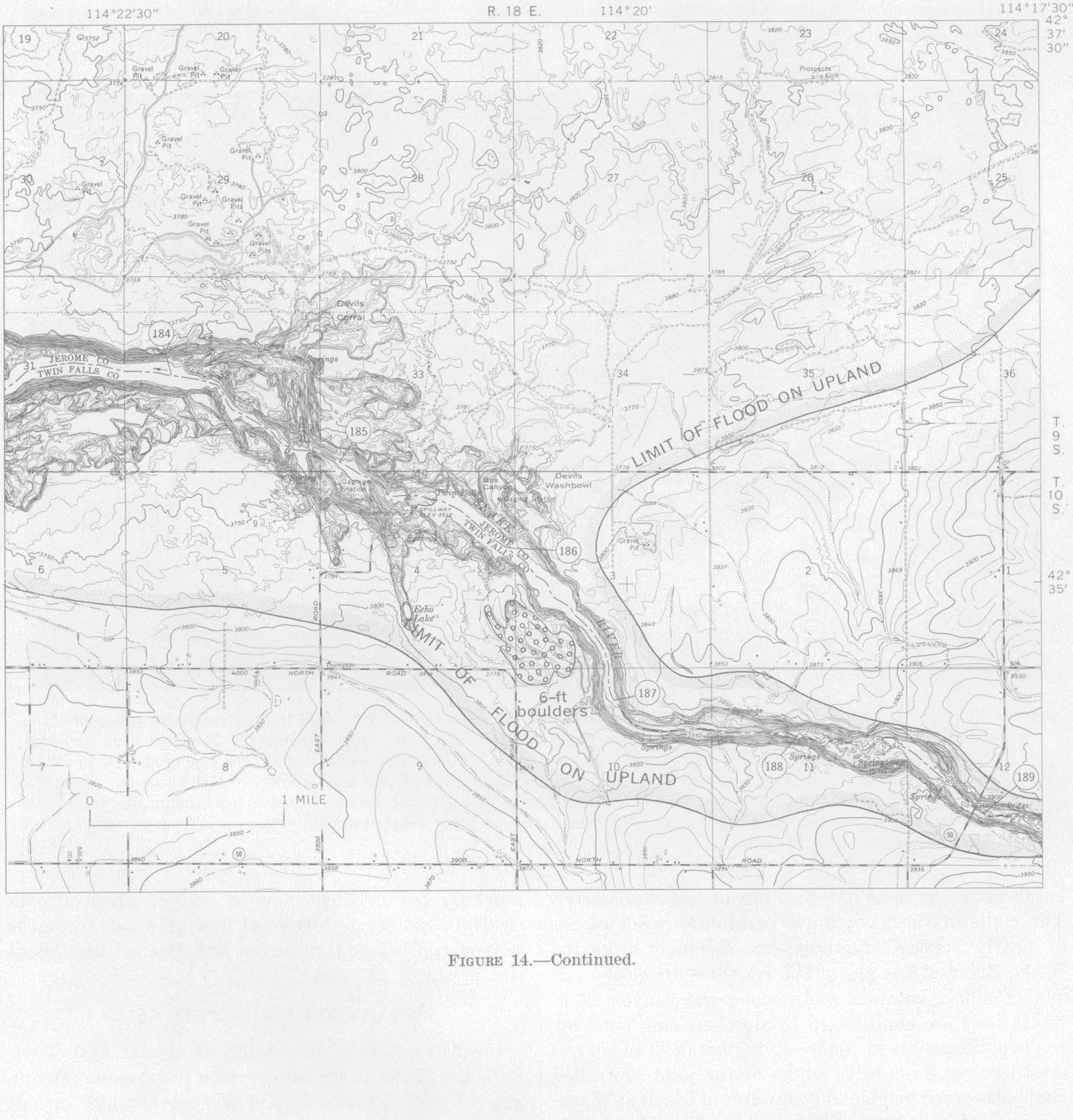


FIGURE 14.—Continued.

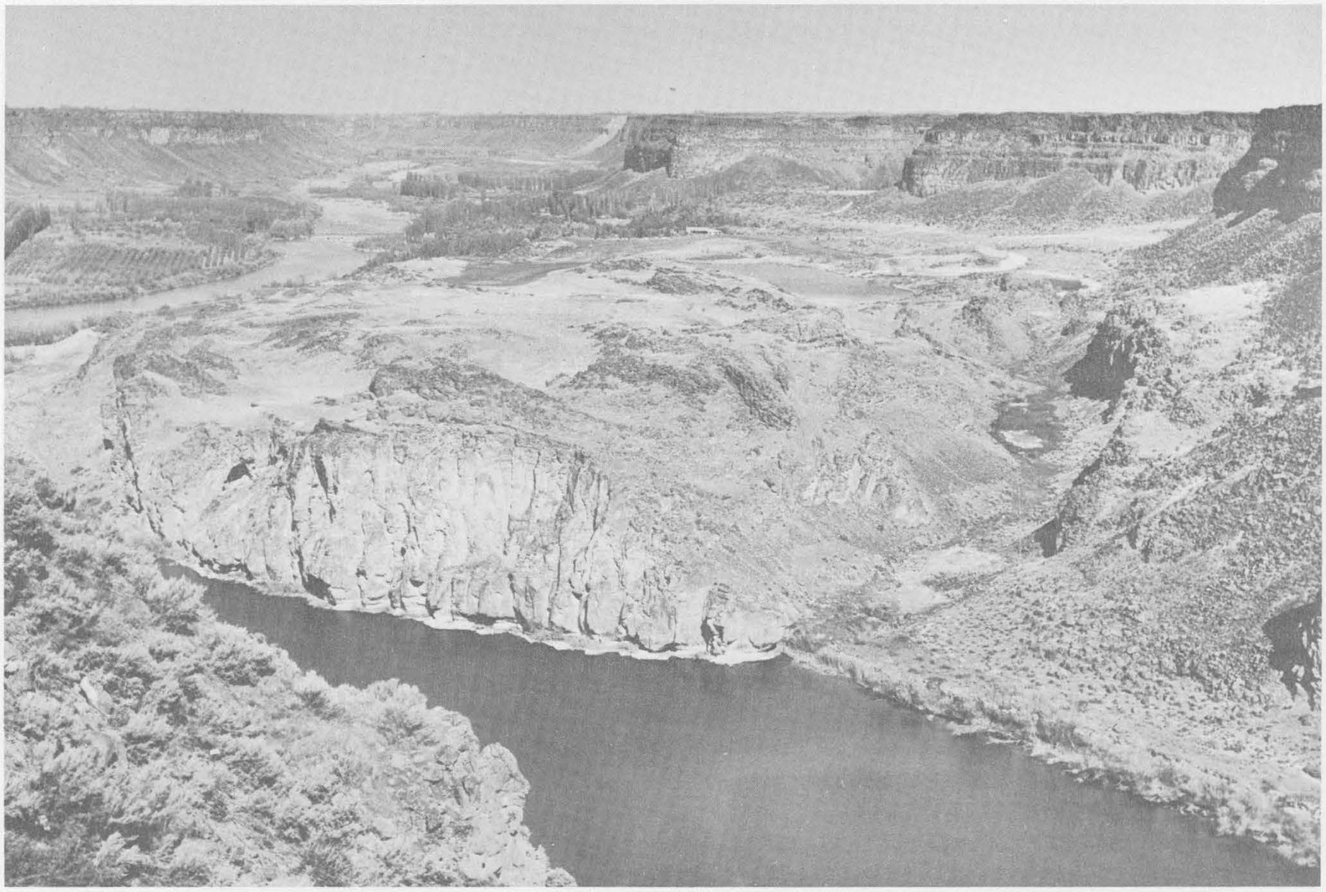


FIGURE 15.—View downstream of Snake River canyon from Perrine Memorial Bridge (mile 180). A massive outcrop of silicic volcanics in the center, rising 200 feet above the canyon floor, was eroded by the Bonneville Flood to form scabland. Embayments in basalt along the northern (right) rim of the canyon mark the mouths of alcoves also eroded by the flood. The orchard at upper left is on a smoothly contoured bar of Melon Gravel that rises about 100 feet above the river. The smooth topography at the golf course beyond the scabland is also built of Melon Gravel. At maximum discharge, this part of the canyon—here 500 feet deep and a mile broad—was probably nearly brimful. (Photograph courtesy of Chamber of Commerce, Twin Falls, Idaho.)

basalt boulders, some of which are 10 feet in diameter. The walls of the alcoves are parallel to weak planes of nearly vertical fractures that obliquely cross the Snake River at this place. The fractures are cleary visible in silicic volcanic rocks along the canyon floor. where they are emphasized by flood erosion, but they are less discernible in the overlying basalt. The alcoves are therefore diminutive copies of the joint-controlled channels carved by glacial floodwater in basalt at Washtucna Coulee, eastern Washington (Trimble, 1950). Because the heads of these alcoves are close to the highest limit of the Bonneville Flood, as determined by scabland, they apparently were first formed by a vigorous crossflow of water, from east to west, which plucked loose blocks from the fractured rock. As erosion progressed, water could drain north into the canyon. The scalloped east edges of the alcoves probably indicate plucking by turbulent flow at eddies. These alcoves clearly demonstrate torrential flow of water above the canyon rim before the canyon had reached its present size.

THE CANYON BELOW TWIN FALLS

Downstream from the region of alcoves near Twin Falls the Snake River has carved a picturesque canyon, generally 500–600 feet deep, which cuts through various sections of basalt and detrital deposits that have controlled the canyon form. In the upper part, from mile 175 to 125, the river drops steeply over a floor of basalt at an average gradient of 11 feet per mile (fig. 3). The route is characterized by intermittent rapids. Thereafter, to mile 0, beyond which the canyon becomes indistinct, the river flows less precipitously on an average gradient of 3 feet per mile. The Snake is therefore one of the steepest large rivers in North America. Because the shape of the canyon at the time of the flood was substantially the same as now and because it greatly influenced the history of the flood, it is worthwhile to summarize the canyon physiography and to indicate some of the flood features along the route.

The canyon below Twin Falls consists of a series of wide segments (basins or coves) that include relatively flat bottom lands not far above the river and that are connected by constricted canyon segments (narrows) of variable length. The basins and narrows are outlined in figure 2 as the area inundated by the maximum rise of the Bonneville Flood. The basins, 20 square miles or more in area, have irregular perimeters. The narrows are about 3,000–4,000 feet wide, measured at the canyon rim.

The canyon shape is a result of two factors—variable erodibility of rocks and enlargement of the canyon at tributary junctions. That is, the constrictions are walled with basalt or are capped with basalt rimrock, generally on both sides; whereas the basins—which commonly coincide with tributary junctions—are carved from nonindurated detrital deposits that readily erode as badlands.

The narrow stretches controlled the flood by impeding flow and thereby impounded water in basins upstream. Because floodwater in most of the basins was about 300 feet deep at highest stage, the basins acted as sediment traps and retained debris flushed down from the canyon upstream (fig. 2). Retarded flow through the basins is demonstrated by a downstream decrease in height of accumulated debris and by a corresponding reduction in size of transported material. Debris piles commonly decrease in height more than 100 feet along the length of a basin, and boulders in the upper reach of basins give way downstream to less bouldery gravel that is rich in sand. Some of the decrease in height of the debris piles and in grain size may of course have resulted from reworking during subsidence of floodwater, but I have discovered no definitive way to discriminate deposits of peak flow from those of possible lesser discharge. The deposits are described in this report only as an overall effect of the flood.

Because the basins were effective traps for sediment transported by the flood and because this sediment is almost entirely basaltic debris derived from outcrops along the canyon, the erosional effectiveness of the flood can be appraised in terms of the volume of debris trapped in basins. This problem is discussed later in this report (p. 44). For the present, I point out only that no material eroded from the upper part of the canyon passed below mile 58, except possibly a little suspended silt, because the exceptionally narrow canyon near Swan Falls (mile 26) impounded a lake that extended 35 miles upstream. This lake prevented further transport of flood debris.

In the following discussion the canyon is divided into successive sections that have distinctive physiographic character and particular features caused by the Bonneville Flood. Some features that are especially indicative of the magnitude of the flood will be elaborated in later parts of this report.

WEEPING WALL SECTION (MILE 175–162)

Immediately downstream from the Twin Falls area, the Snake River enters a straight basalt-walled gorge from 1,500 to 2,500 feet wide at the rim and 450 feet deep, which is here named the Weeping Wall section. A persistent line of springs about 150 feet below the north rim, between a lower unit of decomposed basalt (Banbury Basalt) and a rimrock of rather fresh basalt, gives this canyon segment its name. The canyon is even more constricted than the width and depth would suggest because for nearly half its length it is a two-story canyon. In the upper 6 miles the river flows in a trough 500 feet wide lying 125 feet below a dissected bench of basalt scabland (fig. 3). Melon Gravel at the upstream end of the bench and at the toe suggests that this trough could have been cut since the flood, but erosion by the Bonneville Flood cannot be ruled out. Indeed, at an earlier time H. A. Powers (in Malde, 1960) thought, because of the relation of this canyon segment to basalt older than the flood, that all of the canyon had been cut by flood erosion, but the prior existence of a canyon upstream (the Milner reach) indicates that the Weeping Wall section antedates the flood. In the last 7 miles of the Weeping Wall section, the lower story of the canyon is represented by discontinuous comparatively small bars of Melon Gravel that rise about 100 feet above the river. The gravel lies at river level in some places, and there is no indication of entrenchment since the flood. Because the gravel occurs where the canyon is somewhat wider than it is upstream, deposition of the gravel presumably was caused by a reduced rate of flow.

The Weeping Wall section is joined on the south by Rock Creek and Cedar Draw (miles 174 and 167), but these junctions are not notably enlarged and had no obvious effect on the flood.

A thin mantle of talus along most of the Weeping Wall section indicates that the canyon is only a little wider than during the flood. A projected flood profile, determined by scabland at an altitude of 3,600 feet on the north rim at mile 175 and at an altitude of 3,150 feet at mile 156, would indicate that the canyon was nearly brimful at the highest flood stage. This inference is contradicted, however, by the carrying capacity at mile 172, the narrowest place (fig. 13, section *H–H′*), which is at least four times the capacity at Swan Falls (table 2). The discrepancy can be accounted for if one assumes a flattened profile or a considerable canyon enlargement during the flood.

MELON VALLEY SECTION (MILE 162–155)

Below the long and narrow Weeping Wall section, the river emerges into a small basin called Melon Valley, which is about 2 miles wide and 3 miles long (fig. 16). The depth of the canyon at this place, measured from the north (lower) rim, is from 250 to 300 feet, of which the lower part consists of ragged outcrops of Banbury Basalt that crowd the valley floor. The upper canyon walls consist of resistant fresh basalt on the north rim (Thousand Springs Basalt) and a complex array of interbedded basalt and clastic deposits on the south. Deep Creek and Mud Creek have dissected the south margin of Melon Valley into a rough and gullied terrain. The mouth of Salmon Falls Creek, which joins the canyon near mile 155, coincides with another small basin. The flood profile, reconstructed from scabland at mile 156, indicates that floodwater at peak discharge rose to an altitude of about 3,225 feet at the north canyon rim of Melon Valley (mile 161).

The central part of Melon Valley is covered by a large bar of Melon Gravel 7,500 feet long that rises at midsection to a height of 160 feet above the river (fig. 17, section *G–G′*). Scattered on the surface of the bar, particularly along the crest, are well-rounded basalt boulders that range in maximum diameter from 4 feet at the head of the bar to 2 feet at the toe. A gravel pit at the downstream end of the bar opposite mile 161 affords a cross-sectional view of the internal character. This exposure reveals that the gravel is a mixture of boulders and coarse basaltic sand arranged in thick, crudely bedded sets of inclined layers (fig. 5). The bar is limited on the north by the Snake River and on the south by a marginal channel. Several other boulder bars of lesser size cover much of the remainder of Melon Valley.

Another interesting gravel deposit in this section is at mile 158, the head of an abandoned channel that carried a share of the flood. The surface of the gravel at this place is armored with a layer of 3-foot boulders that display an imbricate fabric in which the boulders dip upstream (fig. 18).

THOUSAND SPRINGS SECTION (MILE 155–151)

This short canyon constriction merits special mention because its discharge capacity indicates the maximum volume of the Bonneville Flood in this reach of the Snake River canyon. The constriction is cut into well-indurated basaltic pyroclastic material and lava flows. The flood height through this section is shown by scabland 240 feet above the river between miles 156 and 154 where a square mile of rimrock on the right bank was scoured and strewn with basalt boulders. The canyon section at the lower end of the scabland (fig. 13, section *F–F′*) has a discharge capacity of 33 million cfs at the indicated height of the flood (table 2), an amount considerably less than the capacity of any place upstream as far as Hansen Bridge (mile 189). Since the flood, the only apparent change in this canyon section has been deposition of pebble gravel, which drilling shows to extend not more than 25 feet below present river level.

Evidently, the constricted section at Thousand Springs was about doubled in size during the flood. The calculated flood discharge is of course limited in accuracy by several obvious uncertainties, but it demonstrates that the constriction at Thousand Springs must have been an important valve that limited the amount of floodwater delivered downstream. Because a larger volume of floodwater would have spread more widely, forming more scabland, the capacity of this constriction also determines the probable maximum discharge that arrived from upstream.

HAGERMAN VALLEY (MILE 151–141)

Hagerman Valley (fig. 19) is a broad canyon segment about 4 miles wide, bounded on the west by spectacular barren cliffs of nonindurated basin deposits (Glenns Ferry Formation) that rise 600 feet above the Snake River and bounded on the east by a lower cliff of basalt. An inner bench of terrace gravel along the east side, standing 300 feet above the river, was the effective canyon wall that limited the spread of floodwater. Scabland upstream at Thousand Springs and Melon Gravel below Hagerman show that the flood surface was at an altitude of 3,030 feet in Hagerman Valley.

Hagerman Valley, containing more than 7 billion cubic feet of Melon Gravel (one-twentieth of a cubic mile), was a major sediment trap for flood debris. (See table 4, p. 45.) The gravel occupies a basaltic substratum 100–150 feet above the Snake River and is spread over an area of about 6 square miles. The greater part of the Melon Gravel is in a huge bar 50–75 feet thick, which covers most of the central area of Hagerman Valley. The bar has a slightly curved trace 3 miles long and extends from mile 151 to the center of the valley near Hagerman. Boulders as large as 5 feet in diameter occur at the upstream end, and 2-foot boulders can be found at the toe. (See fig. 4.) A marginal channel lies along the east side of the bar. The greatest thickness of Melon Gravel in Hagerman Valley, more than

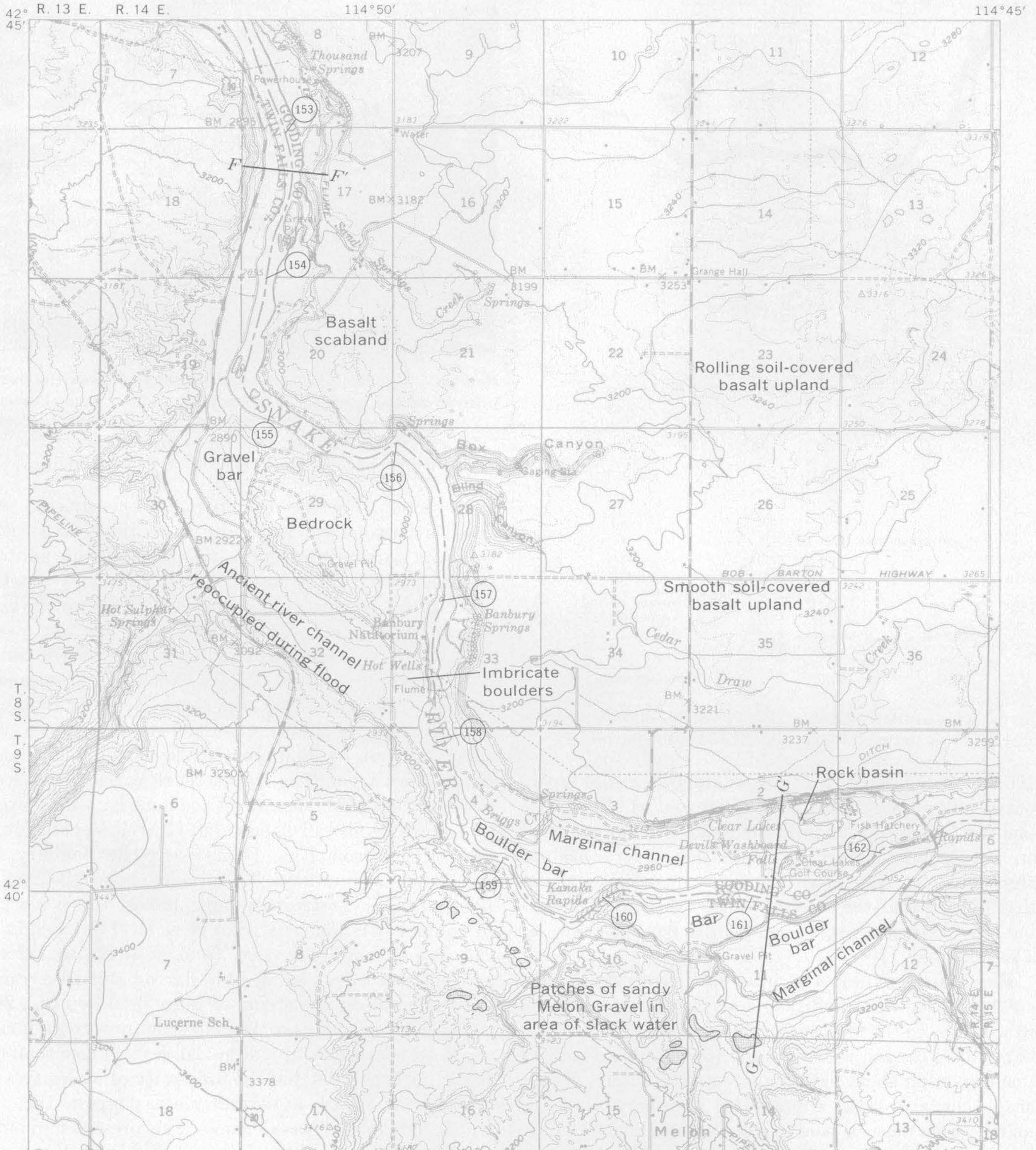


FIGURE 16.—Topographic map of Melon Valley and Thousand Springs area showing features produced by the Bonneville Flood. In Melon Valley a boulder bar extends 1½ miles downstream (west) from a shoulder on the left bank. An adjoining marginal channel heads in a saddle 125 feet above the Snake River. On the north side, a rock basin partly blocked by boulder deposits is carved in Banbury Basalt. Imbricate boulders near mile 158 are illustrated in figure 18. A gravel bar at mile 155 was deposited by floodwater that followed an ancient river channel. Basalt uplands north and east of the river generally stood above the flood, but the rim between miles 156 and 154 was temporarily overtopped by a rise of 240 feet, probably because of the canyon constriction at section *F–F′* (fig. 13). (From U.S. Geol. Survey topographic map of Buhl quadrangle, Idaho, scale 1:62,500; also published in shaded relief as Thousand Springs quadrangle, scale 1:24,000.) (Section *G–G′* shown in fig. 17.)

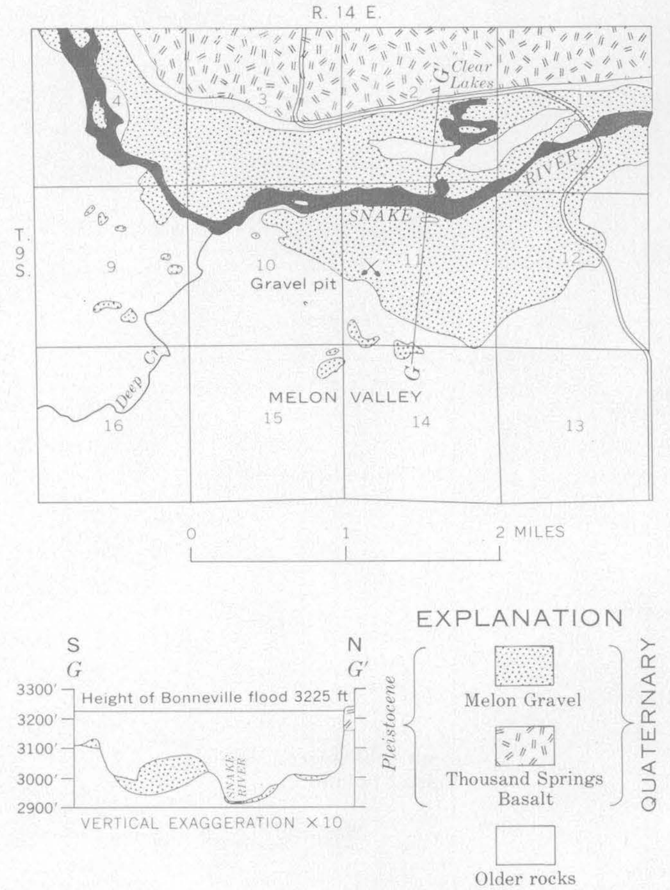


FIGURE 17.—Geologic sketch of Melon Valley, showing location of section through a bar of Melon Gravel.

100 feet, is in a bar that begins at Hagerman and tapers out a mile downstream. The upper end of this bar is tied to a buttress of nonindurated lake clay capped with an unconsolidated terrace gravel that determines the right bank at this place. This circumstance suggests that the force of the flood at Hagerman was dispersed but was nonetheless strong enough to deposit gravel as a pendant bar.

Flood erosion near the head of Hagerman Valley created an unusual hydrologic situation advantageous to wildlife. In the marginal channel between the central bar and the canyon wall, spring water supplies a marshy pond covering about half a square mile. Banbury Basalt crops out at places around the periphery, and the marshy area must be held in a shallow rock basin of the basalt that was scoured out during the flood because the gravel bar is too permeable to act as an effective dam. This area is now maintained as an Idaho State Fish Hatchery and Game Reserve.

BLISS SECTION (MILE 141–121)

Downstream from Hagerman Valley, the Snake River enters another long constriction, here named the

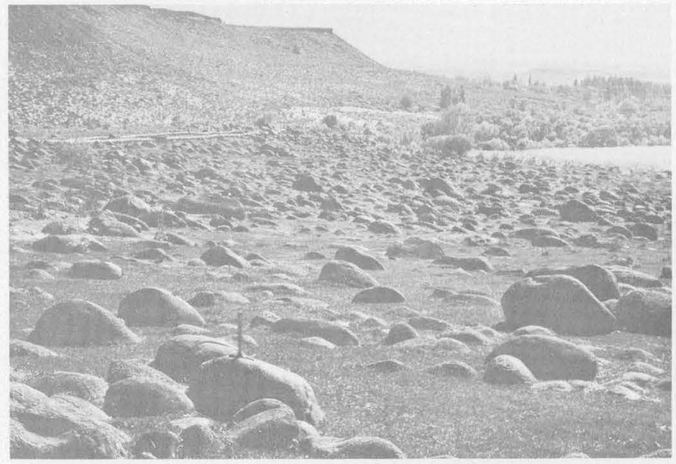


FIGURE 18.—Boulders of Melon Gravel 125 feet above the Snake River at the head of an abandoned channel near Banbury Springs (mile 158). The view is upstream toward Melon Valley. Oblong boulders that dip upstream and toward the axis of the channel (right) express an imbricate fabric.

Bliss section. For the most part, this constricted segment is a two-story canyon in which the Snake River follows a narrow inner gorge, 400–800 feet wide and 200 feet deep, cut mainly into Banbury Basalt. Above the inner gorge is a bench about a mile wide from which canyon walls rise abruptly to a height 575 feet above the river. From Hagerman Valley to mile 135 the bench is largely built of Melon Gravel. From here downstream to Bliss Dam (mile 128), the bench is cut on Banbury Basalt and represents an exhumed erosion surface elsewhere overlain by nonindurated deposits of the Glenns Ferry Formation. The basalt bench carries only scattered patches of Melon Gravel and must have been swept by a forceful flow of floodwater. Gravel is again found downstream from Bliss Dam, where the Banbury descends below river level. This gravel chokes the canyon floor as far downstream as mile 125. It forms a series of boulder bars that rise from river level to a height of 275 feet. Around the bend from mile 124 to 122 the gravel forms a descending set of narrow slip-off terraces, each armored with a string of large boulders (fig. 20).

The Bliss section is somewhat wider now than during the flood because talus and landslides younger than the flood line both sides, but the proximity of Melon Gravel to the canyon walls at several places suggests that the width has not increased much. The present two-story configuration probably also existed during the flood; otherwise, the carrying capacity at the inferred flood height would have been insufficient. Prior existence of the two-story canyon is also indicated by Melon Gravel at river level upstream from the inner gorge.

The Bliss section has some of the largest boulders found anywhere along the Snake River canyon. Boulders on a bench east of mile 136, for instance, are about

8 feet in diameter, and a boulder train that extends from mile 126 to 124 (interrupted by the inner gorge) includes several well-rounded stones that are as much as 10 feet in diameter (fig. 8). These boulders match the lithology of rimrock along the north canyon wall and are probably pieces of talus that were rolled by the floodwater.

Basalt boulders 2–3 feet in diameter and lying 475 feet above the river are found also on the south rim opposite mile 128. These match the lithology of rimrock on the north side, 1 mile distant, and seem identical to some boulders moved by the Bonneville Flood. However, they are 175 feet above the estimated highest stage of the flood and cannot be contemporaneous with Melon Gravel. They must represent a river deposit left before entrenchment of the canyon.

KING HILL BASIN (MILE 121–109)

The King Hill basin is a broad valley 600–1,000 feet deep covering about 35 square miles (fig. 20). The basin is carved almost entirely from nonindurated detrital deposits (mainly Glenns Ferry Formation), but basalt plateaus define the north edge. Two important tributaries enter the basin on the north, Clover Creek and King Hill Creek. Because of its size and because it was the place where the Bonneville Flood first entered relatively slack water impounded by constrictions farther downstream, the King Hill basin trapped a large part of the debris flushed down by the flood. If the debris at Pasadena Valley is included, the basin contains 46 billion cubic feet of Melon Gravel (nearly one-third of a cubic mile), which is more than half the flood debris in the canyon below Twin Falls. (See table 4, p. 45.)

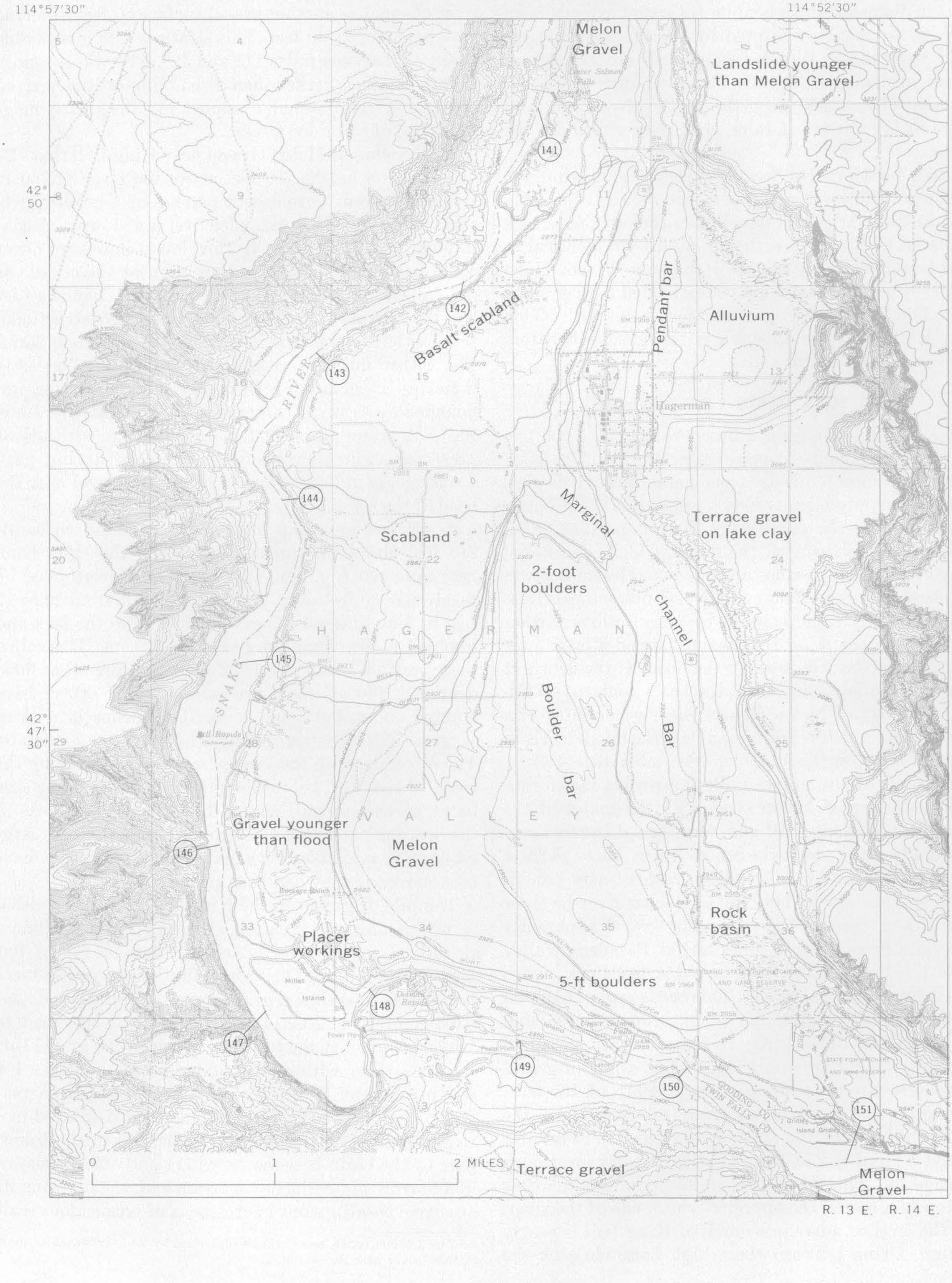
Dumping of the gravel built impressive landforms. Enormous bars of Melon Gravel fill the center of the valley around King Hill and form broad benches several hundred feet above the Snake River. Through these bars the river follows a winding narrow inner trough which reveals that Melon Gravel reaches river level, or lower, along most of the route. The gravel apparently rests on a broad floor. The gravel at Pasadena Valley (mile 121–119) forms a bar about 150 feet thick, which rises 290 feet above the river. This bar is part of a gravel strath that extends another 2 miles downstream into the widest part of the basin. In the wide part, measured around the bight from mile 117 to 110, a pile of gravel covers 6 square miles to an average depth of 160 feet; the highest part is a broad strath 260 feet above the river, which equals the altitude of a possible backwater deposit 2 miles east of King Hill, previously mentioned on page 19. This level (about 2,760 ft alt) matches the top of a bar on the opposite (east) side of the river, and the level of a bar just north of King Hill is nearly as high. Lying between these high bars, close by the river channel, is another gravel surface 60 feet lower, at an altitude of 2,700 feet. This strath is also identifiable upstream between miles 118 and 120. The whole topography, however, rather than resembling ordinary river terraces, is irregular and dissected, like the greatly magnified bed of a braided stream.

The benches of Melon Gravel near King Hill that rise to a common height 260 feet above the river (2,760 ft alt) might seem to represent patches of a graded level surface that formerly extended over a wide area. A continuous gravel surface at this level, however, never could have existed. The benches are near the middle of the valley and are bounded by marginal channels that hug the canyon walls. They are doubtless constructional features left by the flood in virtually their present form. The rather uniform altitude of the benches probably indicates a surface of relatively tranquil water impounded by a canyon constriction at The Narrows (mile 100).[3] A water level 40 feet higher at an altitude of 2,800 feet, which probably was reached during peak discharge, is indicated by the height of gravel near the head of the basin.

A spectacular group of boulders is found on basalt 240 feet above the Snake River along the right bank near mile 120 (fig. 21). This basalt was overtopped by floodwater 50 feet deep. Chunks of basalt from 10 to 15 feet in long dimension were plucked from the lava and tumbled a few hundred feet downstream. The rolled pieces rest on basalt scabland devoid of any other flood debris. A few of them are rounded, and others have blunted edges, but some original pahoehoe lava skins suggest that corrasion during transport was moderate. These boulders are the largest seen anywhere along the route of the flood below Twin Falls and, for their size, lie at an exceptional height. The spacing of cracks in the lava indicates that these rolled pieces were the largest chunks available. Perhaps larger blocks could have been moved if they had been present.

The pile of gravel in the King Hill basin diminishes in height downstream until at mile 112 the maximum altitude above the river is only 200 feet—a fall of 100 feet in 4½ miles. Thereafter the height drops more rapidly. The maximum grain size also diminishes downstream, ranging from 4-foot boulders at the head to 1-foot boulders at the toe. At midlength the gravel surface is strewn with well-rounded basalt boulders 1–2 feet in diameter. In the lower part of the basin a great deal of the flood debris is sand, like that displayed in a large sandbar 125 feet high, constructed in the lowest part of the basin between miles 111 and 109. As shown in a borrow pit at the downstream end, the bar consists of coarse basaltic sand in crossbeds of tremendous scale

[3] The 2,700-ft bench was perhaps controlled by an overflow threshhold at this height at mile 75 (fig. 22).


114°57'30"
114°52'30"
42° 50'
42° 47' 30"
Melon Gravel
Landslide younger than Melon Gravel
Pendant bar
Alluvium
Basalt scabland
Hagerman
Marginal channel
Terrace gravel on lake clay
Scabland
2-foot boulders
H A G E R M A N
V A L L E Y
Boulder bar
Bar
SNAKE RIVER
Gravel younger than flood
Melon Gravel
Rock basin
Placer workings
5-ft boulders
Terrace gravel
Melon Gravel
141
142
143
144
145
146
147
148
149
150
151
0 1 2 MILES
T. 7 S.
T. 8 S.
R. 13 E. R. 14 E.

(fig. 6). These downstream changes in height and grain size surely demonstrate decreased carrying capacity as debris-laden floodwater from the Bliss section met relatively tranquil water in the King Hill basin.

Marginal channels are important physiographic features associated with the deposits of Melon Gravel in the King Hill basin and are comparatively long and deep (table 1). The channels are perched along both sides of the valley as continuous troughs 100–150 feet below neighboring gravel bars. Because they lie close to the canyon walls, the channels emphasize the central valley position of the main mass of gravel. Stearns (1962) identified a pond at the outlet of Pasadena Valley (opposite mile 119) as a plunge pool, but this small depression is only one of several minor irregularities in a marginal channel that winds along the left bank. For instance, Pasadena Valley, a wide place in the upper part of the channel, was under water before it was drained for farming. Such closed depressions are typical of the channels. The channel along the right bank, some 150 feet above the Snake River, continues past the mouth of Clover Creek to the basin edge north of King Hill.

Possible backwater deposits in the King Hill basin and the obstructed tributary at Jolley Flat are mentioned in an earlier part of this report (p. 18).

COVE SECTION (MILE 109–76)

The Cove section of the Snake River canyon consists of a chain of basins (coves) connected by narrow canyon necks. The King Hill basin can be considered as the uppermost cove. Below King Hill the coves are identified as follows: Glenns Ferry basin (mile 108–101), Hammett basin (mile 99–93), Indian Cove (mile 91–87), Eagle Cove (mile 84–81), and Loveridge basin (mile 81–76). All the coves are carved from soft detrital deposits, and most of them coincide with junctions of tributary streams. The connecting canyon necks are for the most part rimmed with basalt.

Only sparse deposits of Melon Gravel are present along the Cove section, and they are mostly sand. (See fig. 24.) Debris flushed from the canyon upstream was almost entirely trapped in the King Hill basin, and the short constrictions between the coves were inadequate sources of additional gravel. Flood debris in the coves forms low bars not more than 75 feet above the river, which are just below constrictions and along the axis of the valley. The greater part of the gravel is in the Glenns Ferry and Hammett basins, and this mostly consists of fine debris that did not get trapped at King Hill. A few basalt boulders at Glenns Ferry were washed through the King Hill basin, and spherical basalt cobbles are rather common. They hinder cultivation and are disposed of in picturesque fences of "petrified melons." The Melon Gravel at Hammett is almost all basaltic sand. Sand also predominates in flood debris downstream, even in Eagle Cove, which lies below a narrow basalt-rimmed canyon neck more than 2 miles long. The Loveridge basin, just beyond, contains no Melon Gravel.

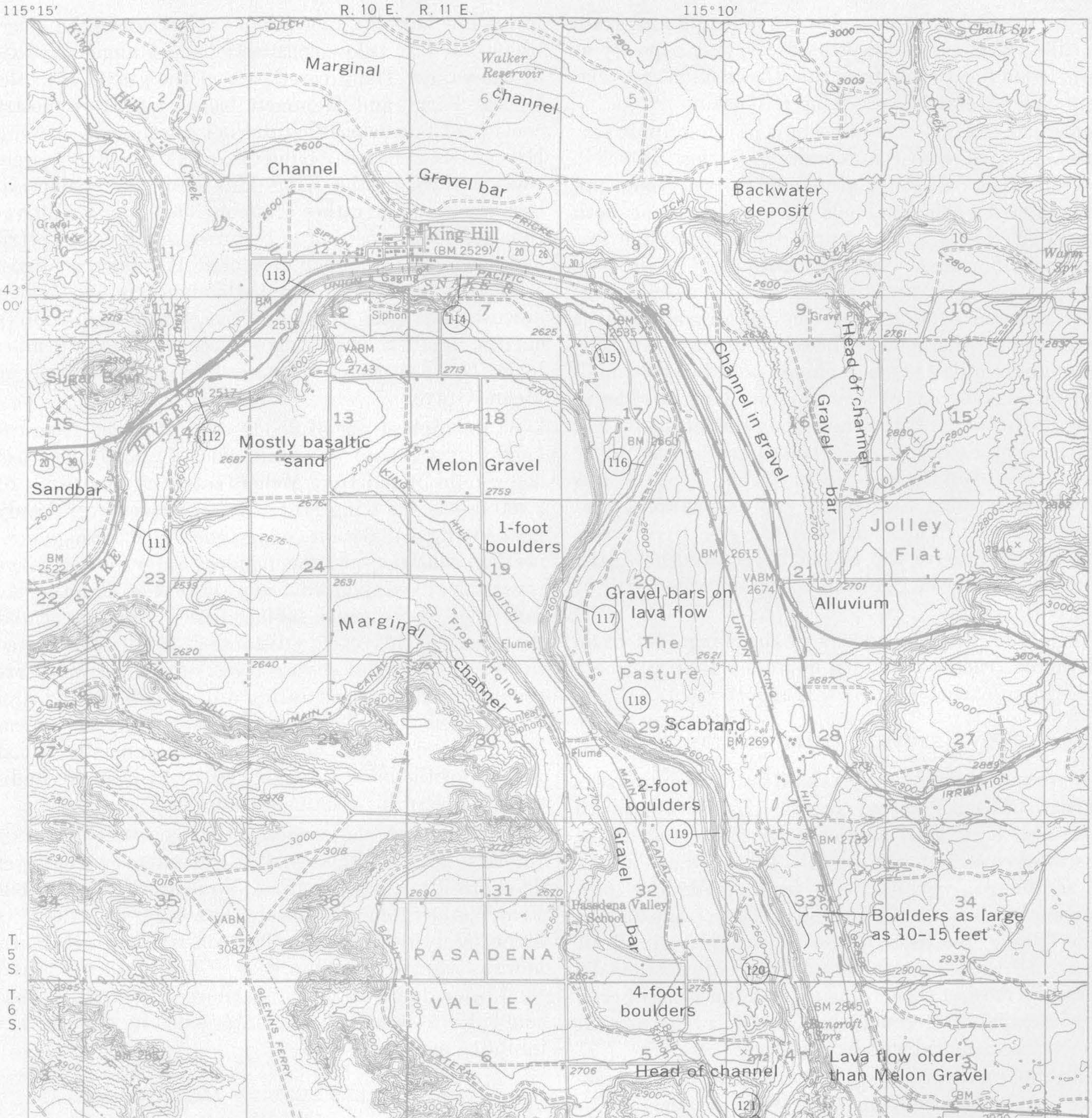
At the highest rise of floodwater, estimated from the height of scabland at an altitude of about 2,740 feet below mile 76 and from Melon Gravel at an altitude of 2,800 feet in the King Hill basin, the coves were deeply ponded (fig. 3). Because of impeded flow through connecting constrictions, the ponded water in successive coves must have assumed a stepped profile. The altitude difference of the water surface between the upper and lower ends of this reach, a distance of 45 miles, amounted to 60 feet. Such descending levels of ponded water are common along streams during ordinary floods and provide a basis for calculating discharge, but this calculation has not been done for the Bonneville Flood because of the more favorable set of hydrologic conditions analyzed by Jenkins near Swan Falls (p. 12).

Flow through the connecting constrictions was fast (at least 20 feet per second at miles 100 and 92), yet flood erosion is not apparent. No debris from the constrictions has been identified in the meager flood deposits immediately downstream. The constrictions are short, however, and are cut into beds of fine-grained silt and sand below the level of basalt rimrock. These soft beds could have been molded into smooth shapes that inhibited erosion.

CRANE FALLS SECTION (MILE 76–61)

The Crane Falls section, a deep basalt-walled gorge, was a major obstruction in the path of the Bonneville Flood (fig. 22). The narrowest place is at mile 75, a slot 1,100 feet wide at the rim and 210 feet deep (fig. 18,

FIGURE 19.—Topographic map of Hagerman Valley, showing features produced by the Bonneville Flood. Bars of Melon Gravel dispersed at the mouth of a constricted canyon segment occupy most of Hagerman Valley and reach 175 feet above the Snake River. Maximum sizes of boulders in these bars decrease rapidly downstream. A bar at Hagerman tied to a projecting mass of lake clay rises 215 feet above the river and obstructs the valley of Billingsley Creek. A rock basin carved by the flood some 2–3 miles south-southeast of Hagerman lies near the head of a long marginal channel that bounds the gravel deposits. Basalt that underlies the gravel of Hagerman Valley is dissected into scabland between miles 144 and 141. Opposite mile 141 a landslide crowds against a strath of Melon Gravel. (From U.S. Geol. Survey topographic maps of Hagerman and Tuttle quadrangles, Idaho, scale 1:24,000.)


115°15′
R. 10 E.
R. 11 E.
115°10′
43° 00′
42° 55′
T. 5 S.
T. 6 S.
Marginal channel
Channel
Gravel bar
Backwater deposit
King Hill
(BM 2529)
Sugar Bowl
Mostly basaltic sand
Melon Gravel
Sandbar
1-foot boulders
Channel in gravel
Head of channel
Gravel bar
Jolley Flat
Alluvium
Gravel bars on lava flow
Marginal channel
The Pasture
Scabland
2-foot boulders
Gravel bar
Boulders as large as 10–15 feet
PASADENA VALLEY
4-foot boulders
Head of channel
Lava flow older than Melon Gravel
Melon Gravel
BLACK MESA
Swiss Valley
Slip-off terraces
SNAKE
111
112
113
114
115
116
117
118
119
120
121
122
123
124
125
0 1 2 MILES

section *B–B′*). As Stearns (1962) pointed out, this gap was too small to contain all the floodwater, which therefore overtopped the canyon walls and partly escaped through a cutoff, rejoining the Snake River at the mouth of the Bruneau River 7 miles west. In entering the cutoff, the floodwater crossed a threshold about 300 feet above the river, as shown by scabland, and the canyon rim at mile 75 was therefore submerged 90 feet. A shorter cutoff, between miles 76 and 73, forms a scabland channel 235 feet above the river, through which water flowed at least 50 feet deep. Still another upland channel diverted water from the Bruneau cutoff, crossed a lip 265 feet above the river, and spilled northward into the canyon at mile 71 to form a deep plunge pool at the toe of a bar of Melon Gravel. Water also spilled northward into the canyon at mile 72 over a horseshoe bend in the canyon rim and carved another plunge pool in Melon Gravel. These plunge pools in gravel that was washed along the canyon demonstrate that the Bruneau cutoff and the canyon were flooded simultaneously. When the Bruneau cutoff was flooded, high water impeded flow through the coves as far upstream as the head of the King Hill basin.

Below the narrow gap at mile 75, the canyon gradually widens and remains a gorge of solid basalt downstream to Crane Falls (mile 73). This stretch, which must have been swept rather clean by the flood, has no Melon Gravel and practically no talus. Below Crane Falls the canyon widens abruptly to about 5,000 feet, and the next 3 miles holds most of the gravel found along this part of the canyon. The gravel is bouldery and forms long narrow-crested bars close to the center of the canyon. Many of the boulders are angular. Because of relatively tranquil flow through the Cove section, this gravel could only have been derived from the narrow gorge above Crane Falls and from scabland along the upland diversion channels. This source is confirmed by lithologic comparison with the local basalt, a distinctive weathered-brown type. The provincial origin of the gravel is of further interest because none of the gravel was carried more than a few miles downstream. Deposition of the gravel implies reduced rate of flow, even though this part of the canyon is relatively steep (7 feet per mile). Buildup of gravel at this place may have been promoted by increased canyon width, but a contributary cause could have been backwater from a temporary lake in the Grandview basin (p. 40). The highest gravel within the canyon is 240 feet above the river (2,640 ft alt) and therefore only 15 feet above the height of ponded water that existed 10 miles downstream.

An interesting patch of gravel is found 250 feet above the river at the lip of the marginal spillway at mile 71. The gravel includes 5-foot basalt boulders derived from scabland to the southeast, and it rests against a vertical face of basalt that bounds the upstream side of the spillway. This anomalous vertical face reaches a height 300 feet above the river and can only be explained by flood erosion. Part of the gravel drapes over the canyon edge and joins gravel 60 feet lower that was washed along the canyon. These relations indicate that floodwater debouching into the canyon at the spillway was about 50 feet deep and had velocity sufficient to accomplish some erosion and to move 5-foot boulders. Moreover, floodwater along the canyon could not have been more than 60 feet below floodwater on the upland.

Owing to ponded water in the Grand View basin downstream, unusual debris deltas were built at the terminus of the Bruneau cutoff (near mile 61, fig. 2). Except for basalt scabland at the upper end of the cutoff and a few projecting knobs of basalt and scattered heaps of basalt boulders toward the lower end, most of the cutoff is a smooth featureless plain of Pleistocene lake deposits marked with no evident sign of the Bonneville Flood. These lake deposits (Bruneau Formation) were the main source of the deltaic debris, which consists chiefly of rounded chunks of diatomite. Two deltas are preserved. The smaller is at the end of a distributary branch terminating at mile 62. The other lies at the end of the main branch near the southeast corner of T. 5 S., R. 4 E., and is well exposed along a deep longitudinal gully in sec. 35.

Exposures along the gully (about a mile long) show that debris carried by the flood washed over a basalt lip and accumulated in layers that dip uniformly westward (downstream) at the rather low angle of 15°. Sets of inclined beds are continuously exposed in places along

FIGURE 20.—Topographic map of King Hill basin, showing features produced by the Bonneville Flood. Slip-off terraces around the bend from mile 124 to 122 are armored with trains of large boulders. Pasadena Valley, which lies near the head of a marginal channel winding along the left bank, is held by a gravel bar that rises 290 feet above the Snake River. On the opposite side, where a lava cliff was overtopped by floodwater 50 feet deep, boulders torn from the lava reach maximum dimensions of 15 feet, as shown in figure 21. The gravel at Pasadena Valley extends downstream into the widest part of the valley where it forms broad straths reaching 260 feet above the river. In this wide area the Melon Gravel obliterates a previous river course that followed a shorter route between miles 118 and 111. The size of material washed into this basin decreases rapidly downstream and at mile 112 consists mostly of sand. Dumping of flood debris obstructed the outlet of Jolley Flat and caused deposition of a broad plain of alluvium. Minor scabland features on basalt near the railroad opposite mile 119 are illustrated in figure 9*A*. (From U.S. Geol. Survey topographic maps of Pasadena Valley and King Hill quadrangles, Idaho, scale 1: 62,500.)

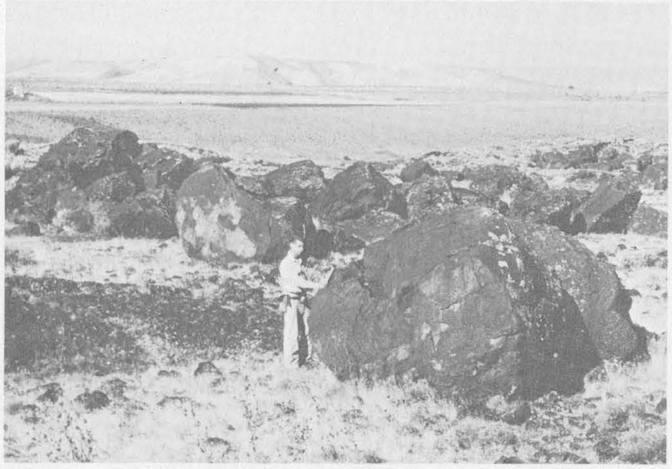


FIGURE 21.—Basalt boulders on lava flow 240 feet above right bank of Snake River near Bancroft Springs (mile 120). The man stands on the lava surface. The long diameter of the rolled block in front of him exceeds 15 feet. The source of these boulders was the lava surface that was overtopped by floodwater a mile or less upstream. This locality was covered by floodwater 50 feet deep. In the middle distance is a strath of Melon Gravel 100 feet below the crest of a long bar that lies beyond. Still farther away are badlands that surround the King Hill basin.

the gully throughout a height of 100 feet. Outcrops of basin deposits (Glenns Ferry Formation) that underlie these beds occur along the gully floor. This pile of debris is therefore draped over the valley wall where floodwater from the Bruneau cutoff entered the Grand View basin and apparently lost velocity. (See also geology mapped by Malde and others, 1963.) The deltaic beds consist of layers dominated by fragmented pieces of diatomite an eighth of an inch or larger in size (commonly pebbles) and of alternate layers rich in basaltic pebbles and coarse sand. These contrasting layers make a striking display of inclined white and gray foreset beds. The beds are as much as several feet thick, and some are marked by intricate festoons of laminated sand such as occur in bars that were deposited in tranquil water of coves upstream. Among the inclined layers are diatomite pieces the size of boulders, and one piece was found that was 12 feet across. Such chunks of soft diatomite could not have survived any great distance of transport. Indeed, their only source was along the Bruneau cutoff not more than 3 miles upstream. The pieces probably were transported as suspended load and were quickly dumped as the velocity slowed. The low density of this debris might account for the low angle of dip of the beds, as compared with the dips of foreset beds in ordinary deltas.

No topset beds can be seen along the gully, but the truncated edges of dipping beds are armored by a level pavement of cobble and boulder gravel, which consists partly of quartzite fragments reworked from nearby Pleistocene gravels and partly of subangular pieces of basalt that must have been carried by the Bonneville Flood. This pavement is from 3 to 5 feet thick where exposed along the top of the gully and lies at an altitude of 2,600 feet. The pavement may have been built by waves chased up the 30-mile fetch of open water in the Grand View basin. E. G. Crosthwaite suggested this origin for the gravel pavement during a field conference in 1962.) When the delta was first built, however, as shown by heaps of basalt boulders dumped near the head, water level in the Grand View basin stood at an altitude of about 2,625 feet. A lack of flood features on a divide 15 feet higher, between this delta and the other to the north, suggests that these boulders accurately mark the maximum level of floodwater in the Grand View basin.

GRAND VIEW BASIN (MILE 61–28)

Below the mouth of the Bruneau, the Snake River enters a broad valley 30 miles long. The valley is bordered on the north by a precipitous wall capped with basalt, but the south edge is lost in badlands carved in basin deposits. Several tributaries join the valley from the south. Buttes of lava in the lower reach of the valley cause the river to wind between constrictions at mile 41 and along a stretch between miles 34 and 28.

At first glance the Grand View basin exhibits nothing attributable to the Bonneville Flood, but this deficiency is its most significant feature—once the magnitude of the flood is appreciated. Melon Gravel forms a small bar no more than 135 feet above the Snake River in the uppermost reach of the basin, between miles 61 and 58; otherwise no flood debris can be found. This lack of debris is a consequence of tranquil flow through a deep lake held by an exceptionally narrow canyon near Swan Falls. The lake had a surface area of 150 square miles, counting the part that must have flooded lower Bruneau Valley, and it had a maximum depth of 325 feet. The depth is demonstrated by the height of boulders associated with deltaic debris at the terminus of the Bruneau cutoff, as just described. (See above.) Ponded water surrounded the lava buttes at the west end, which now confine the Snake River to a narrow canyon along the north edge of the basin.

Tranquil flow of floodwater through the Grand View basin is also suggested by rapid reduction of maximum grain size in the solitary boulder bar just mentioned. The boulders decrease from 4 feet to less than a foot in about a mile and include pieces of nonindurated basin sediments (Stearns, 1952). An abrupt loss in velocity is implied. The bar begins at the mouth of the constricted canyon leading from Crane Falls, and is

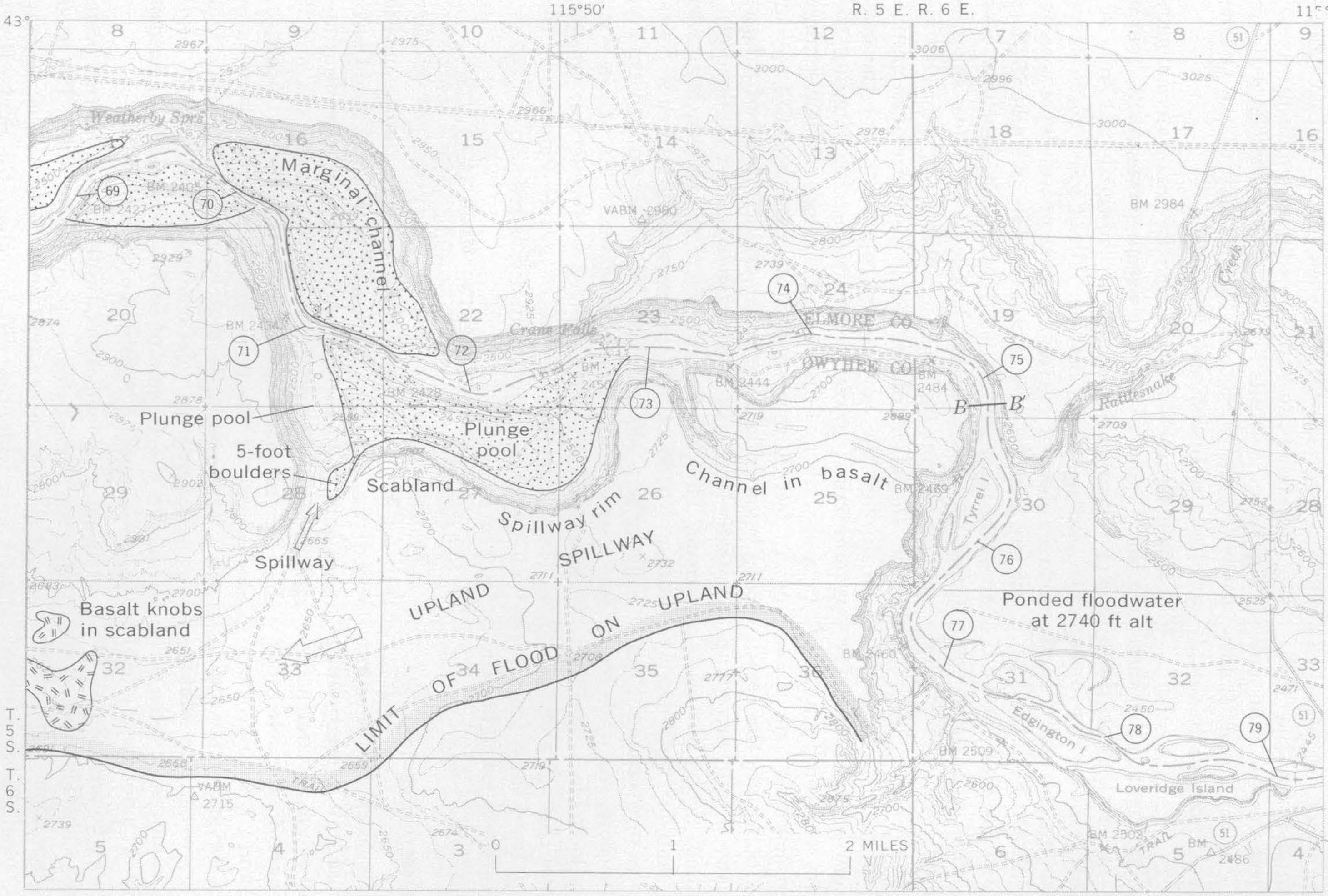


FIGURE 22.—Topographic map of Crane Falls area, showing features produced by the Bonneville Flood. Melon Gravel is indicated by stippel. A canyon constriction at mile 75 caused floodwater to rise and overflow the upland via a cutoff that leads 7 miles westward to the mouth of the Bruneau River. Basalt scabland at the cutoff threshold demonstrates that impounded water stood 300 feet deep upstream at an altitude of about 2,740 feet. Some floodwater returned to the Snake River canyon via a channel in basalt that debouches at mile 73. Water also spilled into the canyon at miles 72 and 71 and formed plunge pools in gravel washed along the canyon. These plunge pools demonstrate that the upland cutoff and the canyon were flooded simultaneously. Basalt boulders plucked from the upland are perched on the rim at the spillway at mile 71. The largest heap of Melon Gravel forms a bar 240 feet high midway between the canyon walls from mile 71 to 70. Owing to ponded floodwater upstream, all the gravel was derived locally. (From U.S. Geol. Survey topographic map of Bruneau quadrangle, Idaho, scale 1:62,500.) (Section *B–B′* shown in fig. 13.)

tied to a shoulder projecting from the north wall. From this shoulder the bar turns abruptly downstream along the interior of a river bend. A pond between the bar and the canyon wall lies at the head of a marginal channel. This bar, rather than being made up of debris transported along the Bruneau cutoff, as Stearns (1962) supposed, includes basalt boulders coarser than any found in the delta at the mouth of the cutoff. It lies where floodwater delivered from Crane Falls would have formed an eddy in the lake.

No flood debris from the canyon upstream, other than a small amount of suspended material, could have passed through the long stretch of ponded water in the Grand View basin. Even the patches of basaltic sand found in the coves upstream are absent. For the upper part of the Snake River, this was the final sump. If some silt did settle to the basin floor, it has been lost among the local badlands and probably has long since been eroded.

The lower end of the Grand View basin is constricted by walls of basalt. The canyon between miles 30 and 28 is only 1,500 feet wide at the rim and could not have carried the flood at the indicated height if some water had not passed around a canyon butte into the mouth of Sinker Creek (mile 28). The canyon walls present an uneven appearance marked by minor nooks, buttresses, and benches—all with smooth rounded outlines. At several places the walls are vertical or overhang. Practically no talus can be found. In short, the walls look to have been plucked clean of any loose blocks and then scrubbed. The height of floodwater through this outlet cannot be determined accurately from these features, but the scrubbed aspect is discernible to a height of at least 250 feet.

SWAN FALLS SECTION (MILE 28–14)

The Swan Falls section is a rock-walled gorge bounded by steep cliffs 600–700 feet high. The adjoining upland rises even higher, and all the floodwater necessarily had to pass this gap. The narrowest places are at miles 26 (fig. 13, section $A–A'$) and 28, where the canyon is about 2,200 feet wide at the top and 650 feet wide at the bottom. These constrictions are cut into solid basalt—a series of thick lava flows at mile 26 and the core of a massive basalt plug at mile 28. At a flood altitude of 2,625 feet, the constrictions at miles 26 and 28 are, respectively, 1,700 feet and 1,900 feet wide. These constrictions acted as the hydraulic dam that impounded floodwater in the Grand View basin. The scrubbed appearance of this stretch of canyon and the lack of flood debris indicate that these constrictions probably acquired their present size during peak discharge. The floodwater no doubt widened the canyon at the narrowest places by removing lava blocks, but it probably did not appreciably deepen the canyon. Downcutting would be evident as a discontinuity in the profile of Sinker Creek where it joins the canyon at mile 28, but this tributary is at grade with the Snake River, and no significant knickpoint can be discerned in its profile upstream. (Topographic details for this part of the flood path are shown by the U.S. Geol. Survey map of the Oreana quadrangle, Idaho, scale 1:62,500.)

Melon Gravel does not occur in important amounts in the Swan Falls section except downstream from a point several miles below the constriction at mile 26. The part upstream, between miles 28 and 26, is swept entirely clean of gravel. The first gravel deposit below the gap is at the west abutment of Swan Falls, 250 feet above the river (mile 23½). This deposit, which includes 6-foot boulders, is at an altitude of 2,575 feet and was used by Jenkins (p. 12) to establish a tailwater altitude in his calculations of a probable discharge of 15 million cfs through the canyon neck upstream. For the next several miles, gravel occurs as patches hugging the canyon walls and distributed through a vertical range of 275 feet. Large amounts of gravel begin to appear only below mile 19, which marks the head of a large centrally located bar that extends another 4 miles downstream. This bar is built where the canyon begins to widen. No doubt the first several miles below Swan Falls, where Melon Gravel is so meager and patchy, was a turbulent fast stretch of water. As will be seen, it must have also been a place of considerable erosion, as shown by the amount of gravel dumped in the Walters basin immediately downstream.

WALTERS BASIN (MILE 14–0)

The wide valley at Walters Ferry was yet another trap for Melon Gravel flushed down by the Bonneville Flood (fig. 23). Debris trapped at Walters could have come only from the constricted canyon extending upstream to the outlet of the Grand View basin, and it therefore gives a measure of flood erosion in this reach. The volume of the flood debris in the Walters basin cannot be measured accurately, owing to its uncertain thickness, but map relations suggest an amount comparable to the volume of Melon Gravel in Hagerman Valley—about one-twentieth of a cubic mile.

The actual extent of floodwater in the Walters basin during the highest stage is poorly determined. The flood passed through a constriction at mile 14 that is only half a mile wide, rose 280 feet above the Snake River to an altitude of 2,535 feet, and overtopped the north rim. Coarse basaltic sand was spread on the upland along a swath half a mile broad that reaches 2 miles northwestward. The further extent of flooded ground

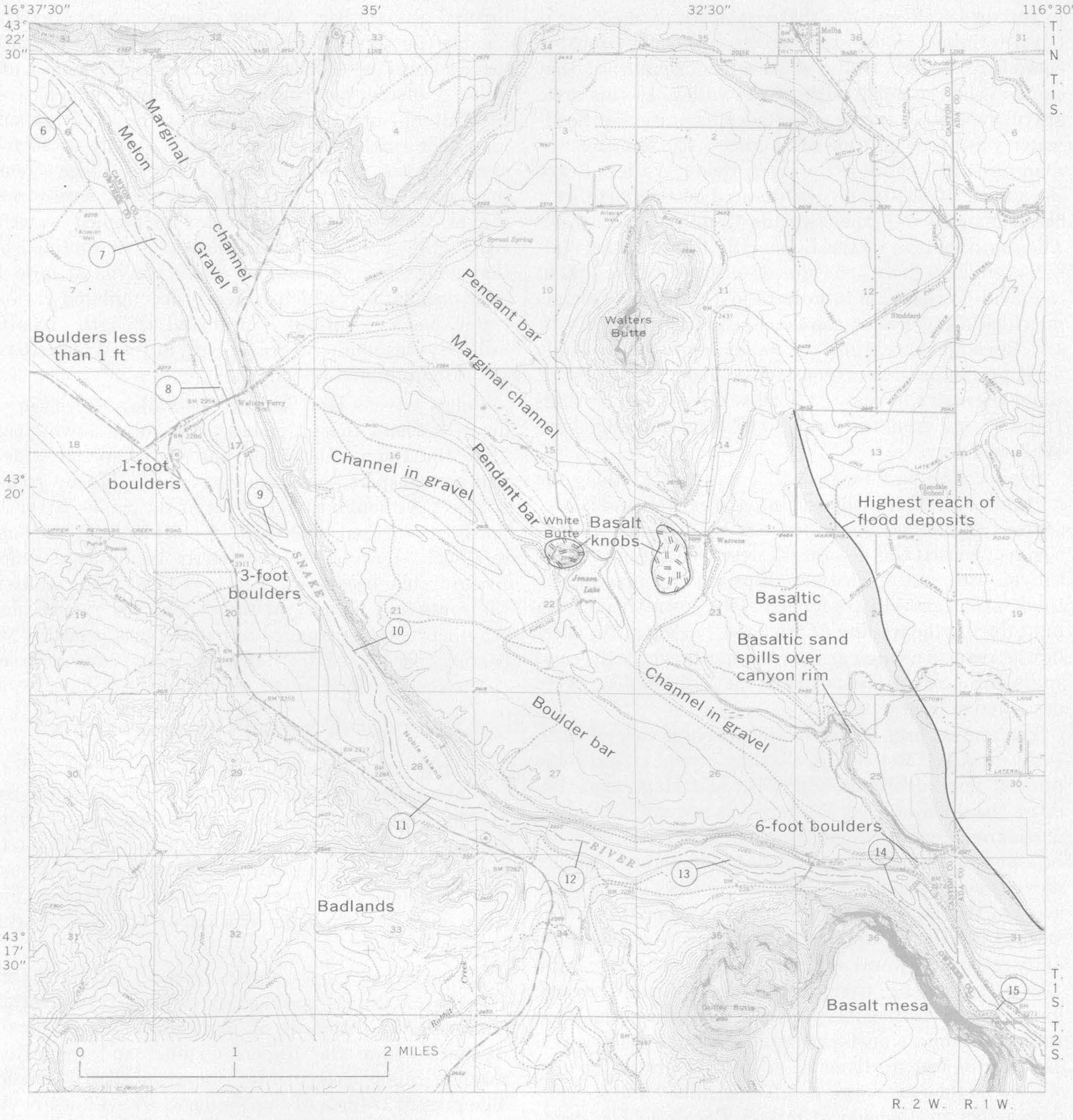


FIGURE 23.—Topographic map of Walters basin, showing features produced by the Bonneville Flood. Floodwater passed a canyon constriction at mile 14 and spread widely, probably surrounding Walters Butte. The canyon rim 280 feet above the Snake River north of mile 14 was overtopped by the flood, and the upland was covered by basaltic sand, of which some spilled back into the canyon opposite mile 13. Bouldery debris that washed downstream forms long linear bars separated by shallow channels. These constructional features trend down the center of the valley to mile 9 and then turn to follow the canyon axis. Some bars accumulated in the lee of bedrock knobs that stood in the path of floodwater. The highest boulder deposits occur several miles below the constriction at mile 14. Maximum sizes of boulders decrease downstream, but large stones are found as far downstream as Walters Ferry. Below Walters Ferry, the volume of flood debris diminishes rapidly. (From U.S. Geol. Survey topographic map of Walters Butte quadrangle, Idaho, scale 1 : 24,000.)

in rolling basalt uplands that rise north of the river is not determined by known deposits, but water probably encircled Walters Butte, a volcanic prominence that stands near the north edge of the valley. In this area, gravel deposits opposite mile 10 demonstrate that floodwater was at an altitude of at least 2,460 feet and was therefore 210 feet above the river. Below Walters Ferry the spread of floodwater was limited on the north by a basalt-rimmed wall that extends 12 miles downstream. The south margin of the Bonneville Flood in the Walters basin is vaguely determined; a basalt wall that held the flood downstream to mile 13 gives way to badlands in which all effects of the flood are lost. Rabbit Creek and Reynolds Creek join the valley here. The probable flood profile has been reconstructed from the height of water necessary to pass the flood at Givens Hot Springs (mile 0) and from the gradient of flood deposits above Walters Ferry.

Some coarse basaltic sand that was carried along the northern upland spilled back into the canyon and is preserved in a small alcove opposite mile 13. Stearns (1962) commented that this deposit is foreset bedded against the canyon wall, but downstream dips are also present. He though that gravel bars immediately downstream were built during the waning of the flood, but a bar 2½ miles downstream is as high as the canyon rim where the sand spills through. It seems likely that all the bars were deposited in deep water.

The central part of the Walters basin is covered with great bars of Melon Gravel that resemble the huge piles of flood debris at King Hill and Hagerman. Because the floodwater at Walters was not impounded by downstream constrictions, however, buildup of this debris was not influenced by impeded flow, and the rapidly moving water had a subtle modifying effect on the character of the deposits. As at Hagerman, flood debris was washed relatively far into the basin so that the crests of bars occur several miles below the canyon mouth. The bars are long, narrow, and streamlined. They are separated by channels that trend directly down the basin rather than by channels that wind along the valley walls. Boulders 6 feet in diameter at mile 14 gradually give way to boulders as large as 3 feet at mile 9 and to boulders a foot in diameter at mile 7. Basalt cobbles occur at Givens Hot Springs (mile 0). All these relations suggest forceful flow. Nevertheless, as at other basins along the canyon, the average size and the quantity of flood debris decrease rapidly downstream. Most of the debris at Walters Ferry (mile 8) is sand, and the quantity of debris washed beyond Walters Ferry is small.

Knobs of basalt in the northern part of the Walters basin had an important effect on the shape of the gravel deposits, which are strung out downstream in long tapered pendant bars. At least three such bars are recognizable (fig. 23). The largest, in the lee of White Butte, has a closure of 60 feet at the head and a length of 2 miles. A smaller pendant bar that hangs from a buttress of Walters Butte has a closure of 30 feet and is a mile long. The smallest bar, which has a closure of 40 feet, is attached to a basalt knob at Warrens. These streamlined bars differ from the rather broad, level-topped gravel deposits that accumulated in ponded water at King Hill. They are comparable to a streamlined bar that hangs from a shoulder in the canyon at mile 18. This pendant bar, which evidently accumulated in rapid water, has a closure of 80 feet and a length of half a mile. By this analogy, gravel bars in the Walters basin indicate high flow velocities.

Below Givens Hot Springs the valley widens into a broad lowland that stretches many miles downstream. Here the Bonneville Flood must have spread widely, and its transport power must have been thereby greatly reduced. Although this segment of the Snake River has not been searched intensively for evidence of the flood, any such signs would necessarily be faint, if indeed recognizable, because of a lack of hard material along the route and because of the diminished rate of flow. Any debris that managed to pass Givens probably was carried only a few miles downstream, but even at Givens the amount of flood debris was small.

BUDGET OF EROSION AND DEPOSITION

Comparison of the volume of Melon Gravel with the size of the canyon upstream provides a basis for estimating the probable amount of erosion caused by the Bonneville Flood. Such an estimate is possible for the upper part of the canyon because no significant quantity of flood debris passed through the Grand View basin and because later erosion of the gravel seems inconsequential.

The enlarged canyon segment near Twin Falls (mile 175–189), with its spectacular alcoves, cataracts, and bordering scablands, is of particular interest because discharge from the Rupert channel and the Milner reach at this place evidently caused substantial erosion. The present volume of this segment, which must closely approximate the volume when the flood subsided, is computed to be about 60 billion cubic feet, or four-tenths of a cubic mile (table 3). From this volume must be subtracted the original canyon volume so as to yield an estimate of erosion actually accomplished by the flood. I assume that the original canyon size near Twin Falls may have been as large as an average between the extremes represented by canyon dimensions above and below the enlarged segment, but I further assume that the canyon may have been as small as the size just suffi-

TABLE 3.—*Computation of volume of Snake River canyon, Augur Falls (mile 175) to Hansen Bridge (mile 189)*

Altitude interval (feet above sea level)	Volume (cubic feet×10⁹)	
	Interval	Total
Augur Falls to Perrine Memorial Bridge (mile 175–180)		
3,100–3,200	3. 0	37. 2
3,200–3,400	14. 2	
3,400–3,600	20. 0	
Perrine Memorial Bridge to Shoshone Falls (mile 180–183)		
3,150–3,300	1. 9	11. 9
3,300–3,400	1. 9	
3,400–3,500	2. 4	
3,500–3,600	2. 8	
3,600–3,700	2. 9	
Shoshone Falls to Twin Falls (mile 183–186)		
3,350–3,400	0. 3	6. 5
3,400–3,500	1. 1	
3,500–3,600	1. 8	
3,600–3,750	3. 3	
Twin Falls to Hansen Bridge (mile 186–189)		
3,500–3,600	0. 6	4. 9
3,600–3,700	1. 4	
3,700–3,800	1. 4	
3,800–3,900	1. 5	
Total		60. 5

cient to contain all the floodwater. Thus, I calculate lower and upper limits of flood erosion, as follows.

An average cross-sectional area of the original canyon, based on an area of 160,000 square feet at mile 189 (fig. 13, section *J–J′*) and an area of 490,000 square feet at mile 172 (section *H–H′*), may have been about 320,000 square feet. Such a canyon 14 miles long would have had a volume of 24 billion cubic feet, and the inferred lower limit of flood erosion would have been 36 billion cubic feet, or one-fourth of a cubic mile. For the upper limit of erosion, an original canyon large enough to carry the flood (probable discharge of 15 million cfs) at a gradient of 27 feet per mile may have been 300 feet deep and would have had a trapezoidal cross-sectional area of 150,000 square feet, if a roughness coefficient of 0.03 is assumed. This smaller canyon would have had a volume of 11 billion cubic feet, and flood erosion would have amounted to about 50 billion cubic feet, or one-third of a cubic mile.

When solid rock is broken into gravel, a volume increase occurs because of increased porosity. If a porosity of 25 percent is assumed for Melon Gravel (Manger, 1963, p. E41), 36 billion cubic feet of basalt would yield 48 billion cubic feet of gravel, or one-third of a cubic mile; and 50 billion cubic feet of basalt would yield 67 billion cubic feet of gravel, or nearly half a cubic mile.

The volume of gravel actually found as far downstream as Grand View is estimated to be 84 billion cubic feet, or nearly six-tenths of a cubic mile (table 4). Thus, the enlarged canyon segment near Twin Falls, whatever is assumed about its original size, appears to have produced the major part of the Melon Gravel. Furthermore, if gravel below Crane Falls is ignored—because it was evidently derived from nearby outcrops—the canyon near Twin Falls takes on added importance as the major source of Melon Gravel. The excess of gravel over what can be attributed to erosion near Twin Falls probably came partly from sources still father upstream but chiefly from constricted places along the canyon downstream, as will now be discussed.

TABLE 4.—*Volume of Melon Gravel above Grand View*

Canyon segment	Miles along river	Volume (cubic feet×10⁹)
Perrine Memorial Bridge to Melon Valley	180–163	1. 4
Melon Valley	163–159	2. 9
Melon Valley to Hagerman Valley	159–150	1. 0
Hagerman Valley	150–141	7. 3
Bliss section	141–121	5. 9
King Hill basin:		
Pasadena Valley	121–118	6. 3
South of river	118–109	26. 5
East of river	118–115	3. 9
North of river	115–111	7. 5
Near Sugar Bowl	111–109	1. 9
Glenns Ferry basin	109–100	7. 2
Hammett basin	99–93	4. 1
Indian Cove	91–86	1. 4
Eagle Cove	83–80	. 2
Crane Falls to Grand View	74–58	6. 4
Total		83. 9

The distribution of Melon Gravel below Twin Falls, represented graphically in figure 24, together with the occurrence of boulders, gives clues for evaluating the canyon as a source of flood debris. Although some gravel was lodged in upstream basins such as Melon Valley and Hagerman Valley and a little was distributed along constricted sections, major amounts were not deposited until the debris reached the first stretch of ponded water, namely the King Hill basin. Because large boulders were rapidly reduced during passage downstream and because the existing boulders came from nearby outcrops, much of the material eroded at Twin Falls must be represented by sand. Most of the sand probably was swept into the King Hill basin, and diminishing amounts settled out in the string of coves downstream. The bouldery component of the gravel, which is conspicuous in the upper part of the canyon and along certain constricted places, therefore can be attributed mainly to local erosion along the canyon. Boulders constitute about 20 percent of the flood debris and imply

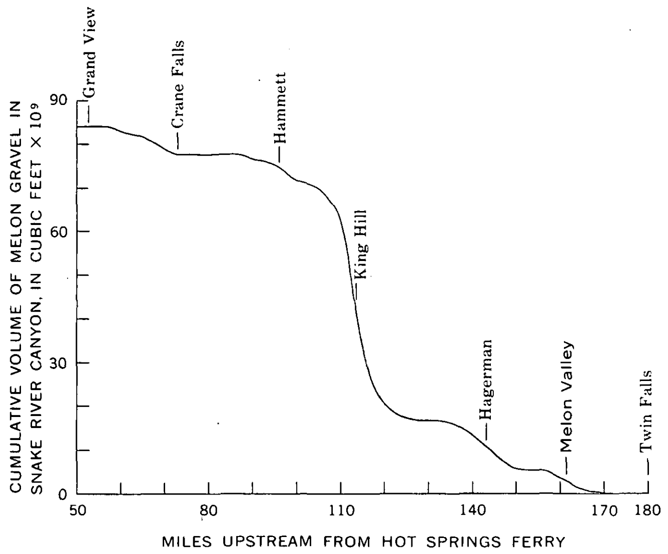


FIGURE 24.—Graph showing volume of Melon Gravel along Snake River from Twin Falls to Grand View.

an equivalent volume of canyon erosion. Moreover, because the Twin Falls segment fails to account for all the remaining nonbouldery component of Melon Gravel—unless the calculated upper limit of erosion at Twin Falls applies— some additional canyon erosion beyond that indicated by the boulders must have occurred. Despite the amount of inferred canyon erosion, however, simple arithmetic shows that enlargement at any particular segment of the many miles of canyon below Twin Falls must have been small. During passage of the Bonneville Flood, the canyon physiography probably was modified more importantly by deposition of Melon Gravel. In short, even though the canyon below Twin Falls was somewhat enlarged by flood erosion, it probably closely resembles its aspect just prior to the Bonneville Flood.

DISCHARGE AS INDICATED BY SIZE OF BOULDERS

Hydraulic engineers distinguish between two kinds of sediment movement by streams: the "bedload" consisting of larger particles that slide and roll along the bed and the "suspended load" consisting of smaller particles transported in suspension. The proportion between these sediment components depends on the velocity of flow and on grain size. If the velocity does not exceed a certain small value, all the sediment moves in contact with the bed, whereas a sufficiently high velocity may cause even the largest particles to move in suspension. If sediment of mixed sizes is supplied to a stream, the coarse particles ordinarily will move along the bed, whereas the finer particles flow past; below a critical traction velocity, the coarse particles cease to move. The larger particles along the bed of a stream are therefore indicators of former maximum velocities of flow. Bruun (1962, p. 43–67) summarized what is known about sediment transport in alluvial channels.

Observations of traction velocities generally have depended on measurement of sand and fine gravel in laboratory flumes and in some large waterways. No experiments have been made with material as large as some of the boulders in the Melon Gravel nor have there been any experiments made with material as poorly sorted. The largest pieces moved by streams for which data are available measure less than 2 feet. (For data on weight of stones used in constructing coffer dams in flowing water, see Torpen, 1956, p. 61.) Any calculation of velocities based on larger particles is therefore a considerable extrapolation. For example, Trimble and Carr (1961a, p. B166) estimated that 8-foot boulders found at Pocatello indicate a velocity for the Bonneville Flood of from 16 to 48 mph (miles per hour) or 24–70 fps.

Velocities necessary to move boulders found in the Melon Gravel have been computed in tables 5 and 6 by use of two formulas that give somewhat different values. The U.S. Bureau of Reclamation (USBR) formula, which relates bedload velocity to grain size (Peterka and others, 1956) is based on a study by Berry (1948), who summarized numerous reports of the transport

TABLE 5.—*Velocities and discharges indicated by size of boulders in Melon Gravel just below canyon constrictions*

Location	Mile on river	Maximum boulder size (ft)	Velocity (USBR)[1] (fps)	Velocity (Nevin-Hjulström) (fps)	Cross-sectional, area of constriction (sq ft×10⁵)	Discharge based on lesser velocity (cfs×10⁶)
Upper Melon Valley	162	4	18	17	1.0	17
Banbury Hot Springs	158	3	15	15	.8	12
Upper Hagerman Valley	150	5	20	19	1.0	19
Bliss	136	8	25	22	.6	13
Swiss Valley	124	10	28	24	.6	14

[1] U.S. Bureau of Reclamation.

TABLE 6.—*Velocities indicated by size of boulders in Melon Gravel where floodwater was not constricted*

Location	Mile on river	Maximum boulder size (ft)	Velocity (U.S. Bur. Reclamation) (fps)	Velocity (Nevin-Hjulström) (fps)
Eden		10	28	24
Bancroft Springs	120	12	31	26
King Hill basin	117	2	13	13
Glenns Ferry	107	1	9	10
C. J. Strike Dam	60	4	18	17
Walters Ferry	9	3	15	15
Givens Hot Springs	0	½	6	8

power of streams, including one on the movement of particles as much as 6 inches in diameter. The formula can be expressed as $V_b=9\times d^{1/2}$, where V_b is the bed-load velocity in feet per second and the diameter, *d*, is in feet. The Nevin-Hjulström formula is derived from a plot of data by these authors, reviewed by Fahnestock (1963, fig. 30) and expressed as $V_t=10\times d^{1/2.6}$, where V_t is the traction velocity in feet per second and the diameter, *d*, is in feet. The particle size in the USBR formula depends on the square of the velocity (the "sixth power law"), but the particle size in the Nevin-Hjulström formula varies as the 2.6 power of the velocity. Thus, the Nevin-Hjulström formula attributes a greater competency to streams than the sixth-power law would predict.

The velocities calculated by both these formulas may be larger than was actually required to move boulders found in the Melon Gravel. For instance, in a bouldery glacial stream, Fahnestock (1963, p. A30) caught some stones 1.8 feet in diameter that were moved by water flowing 7 fps. Also, in flume experiments, a flow of 4 fps was sufficient to move stones about half a foot in diameter along a bed of sand (Fahnestock and Haushild, 1962).

Movement of large pieces at unexpectedly low velocities may be a consequence of mixed sizes in the stream load. The water of flooded streams heavily laden with sand is relatively dense, and its transport capacity is greatly increased (Segerstrom, 1950, p. 108–113; fig. 54). The Snake River during the Bonneville Flood evidently was loaded with sand, and this burden may have increased its capacity to move boulders. In less turgid streams, fine particles fill irregularities on the bed and permit larger particles to move more readily. For such streams, Fahnestock (1963, p. A30) points out that "one can expect * * * erosion [that is, movement] of particles larger than those predicted by formulas based on data for uniform materials." However, stones move along rocky glacial streams as easily as along sandy streams (Fahnestock and Haushild, 1962).

If the height of floodwater is known, flow velocities indicated by large boulders deposited just below canyon constrictions should give a measure of discharge. At places in the upper part of the Snake River canyon where the flood profile can be reconstructed from geologic evidence and constricted sections can be measured, the flow velocities indicated by boulders suggest discharges comparable to the canyon capacity computed near Swan Falls (table 5). Boulders in Melon Gravel therefore seem to be rather accurate indicators of velocity of flow. This result is of interest because unexpectedly large boulders are found at some wide places along the canyon (table 6). If these boulders indicated average velocities through the wide sections during highest flood stage, very large discharges would be demonstrated. Such aberrant boulders occur in isolated groups strung out along bars and evidently represent zones of fast currents that swept large stones into basins—not high average velocities. The rapid reduction in particle size commonly observed elsewhere in such basins, as at King Hill and in the upper reach of the Grand View basin, probably can be considered as an accurate model of retarded average flow.

Finally, the structural habit of the local basalt imposes restrictions on inferences drawn from sizes of transported debris. If the dimensions of basalt columns and the size of talus blocks limited the size of flood debris, no boulders larger than about 5 feet would be found, regardless of the power of the flood to move bigger pieces. However, the surfaces of lava flows, heaved locally into pressure ridges of coherent blocks about 15 feet across, also supplied material for transport. Such lava flows were washed by the flood in the Rupert channel (near Eden) and on the canyon rim above Bancroft Springs (mile 120), and they exhibit a few rolled boulders nearly as large as the available blocks. Within the canyon, on the other hand, close spacing of columnar joints mainly determined the size of boulders—except for a few large talus blocks dislodged from lava surfaces. Thus, the size of boulders may indicate only a minimum velocity of flow. For example, tremendous average flood velocities at Thousand Springs and Swan Falls—which are respectively calculated as 34 and 37 fps from the cross-sectional areas—impinged on columnar-jointed basalt and are underrated by the size of debris found immediately downstream.

COMPARISON WITH HISTORIC FLOODS

The Bonneville Flood so greatly exceeded the ordinary experience of river behavior that it can be compared only with catastrophic floods, particularly those caused by failure of reservoirs or by rupture of natural dams of earth and ice. Such floods have produced brief discharges about as large as the Bonneville Flood, but none have lasted as long. A few historic floods of this kind are summarized here. (See also, Hutchinson, 1957, p. 42–56; and Barrows, 1948, p. 136–137.)

RESERVOIR FAILURES

GÓHNA LAKE, INDIA

In early September 1893, landslides at Gohna, India, blocked the river Bireh Ganga, a tributary of the Ganges, and formed a lake more than 800 feet deep (Holland, 1894). The Indian Corps of Engineers took charge, predicted the probable time of overflow, and established a warning system to prevent loss of life (Strachey, 1894). Rupture occurred about a year later, August 25, 1894, when the reservoir contained 16½ billion cubic feet of water (one-ninth of a cubic mile). Observers trying to witness the actual burst were frustrated by rain and darkness (Lubbock, 1894), but 4½ hours later the water level had fallen 390 feet and the lake had discharged more than 10 billion cubic feet. Contemporary accounts (Glass, 1896; Frizell, 1901) accurately recorded the progress of the flood wave as given in table 7. It appears that, although the average discharge during the first 4½-hour period was 620,000 cfs, the initial flow must have been much greater, undoubtedly several million cubic feet per second. The computed flow velocity, even 150 miles downstream, was comparable to estimated velocities of the Bonneville Flood. No information is available concerning the size of material moved by the Gohna flood.

TABLE 7.—*Flood wave on the Ganges caused by rupture of landslide dam at Gohna, India*

[Modified from Barrows, 1948, p. 7]

Distance from reservoir (miles)	Maximum rise above normal river (feet)	Beginning of rise			Maximum rise		
		Elapsed time	Miles per hour	Feet per second	Elapsed time	Miles per hour	Feet per second
Just below reservior	260						
13	160				25^m	31	45
20		47^m	25	37			
30	130	1^h20^m	22	32	2^h15^m	13	19
51	140	2^h30^m	20	29	4^h15^m	12	18
72	42	3^h45^m	19	28	5^h10^m	14	20
150	11	9^h15^m	16	23	12^h	12½	18

THE GREAT INDUS FLOOD, INDIA

In the winter of 1840–41, part of the Lechar spur of Nanga Parbat collapsed into the Indus River. This dam impounded a temporary lake 1,000 feet deep and nearly 40 miles long. Early in June the barrier was overtopped, and in 24 hours the lake emptied, sweeping everything before it. The meager records of this great flood have been compiled by Mason (1929, p. 15–17). At Attock, 260 miles downstream, the water rose about 100 feet, with an immediate rise of nearly 80 feet. A Sikh army encamped close to the river near Attock was overwhelmed by an "absolute wall of mud." Mason quotes from an eyewitness account,

> It was a horrible mess of foul water, carcasses of soldiers, peasants, war-steeds, camels, prostitutes, tents, mules, asses, trees, and household furniture, in short every item of existence jumbled together in one flood of ruin * * *. As a woman with a wet towel sweeps away a legion of ants, so the river blotted out the army of the Raja.

The actual volume of water discharged by the Great Indus Flood is not known, but Mason gives dimensions of the barrier that would indicate a volume of at least 40 billion cubic feet (more than one-fourth cubic mile). The release of this volume within 24 hours would indicate an average discharge of 500,000 cfs, but the height of the flood wave at Attock suggests an initial discharge several times greater.

FLOOD AT GROS VENTRE, WYOMING

On June 23, 1925, a mass of rock loosened by heavy rains slid into the Gros Ventre River valley, Wyoming, and formed a dam from 225 to 250 feet high (Alden, 1928). A lake grew rapidly behind the barrier, but overflow did not occur until May 18, 1927. Erosion at the dam rapidly lowered the lake level 50 feet and released 1.9 billion cubic feet of water. Limestone blocks 15–20 feet in diameter were moved some distance below the dam. The village of Kelly, 4 miles downstream, was overrun by a wall of water 15 feet high, and the flats below Kelly were flooded to a depth of 10–14 feet. Five hours after overflow the flood had passed, and the stream had receded within its banks. The flood was felt the next day as far downstream as Idaho Falls, about 150 miles away, where the discharge was 60,000 cfs (U.S. Geological Survey, 1959, p. 31, data at Heise).

LAKE ISSYK, U.S.S.R.

On July 8, 1963, a mudflow rushed down a precipitous valley on the north side of the Transilian Alatau and entered Lake Issyk (lat 43° N., long 77° E.), a body of water 1.5 kilometers wide, 1.8 kilometers long, and 50 meters deep (Gerasimov, 1965). High waves produced by the violent mudflow surged over the lake's barrier, a landslide dam, and caused rapid erosion. Huge blocks of rock began to move, and material from the dam poured down the Issyk valley. The lowland at the foothills was transformed beyond recognition by deposition of a wide uneven boulder-covered field, and a terrace 20 meters above the original valley floor was destroyed. Passage of this debris was accompanied by erosion along the valley walls; bedrock formerly concealed by alluvium was thereby exposed. The catastrophic outflow continued more than 5 hours, and the lake drained completely in 24 hours. At the end, an outlet channel 70 meters deep, 100 meters wide, and 800 meters long had been cut through the landslide dam.

ST. FRANCIS DAM, CALIFORNIA

St. Francis Dam, a structure 205 feet high about 45 miles north of Los Angeles, failed suddenly about midnight March 12–13, 1928, and released 1.6 billion cubic feet of water at a maximum rate of from 400,000 to

500,000 cfs. (For a popular account of this disaster, see Outland, 1963.) The failure of the dam prompted intensive studies by geologists and engineers. The flood wave moved rapidly downstream (table 8) at a speed comparable to the inferred velocity of the Bonneville Flood. Exceptionally large velocities just below the broken dam are suggested by transport of colossal concrete blocks some distance downstream. For example, a block weighing 10,000 tons was washed 3,000 feet below the dam, and smaller pieces of the dam were carried almost a mile. Bowers (1928, fig. 4) shows a map of the dislodged blocks and reconstructs their original position in the dismembered structure. To a person standing among these blocks, the awesome power of such rapidly moving water would seem invincible.

TABLE 8.—*Progress of flood wave from St. Francis Dam, Calif.*

[Modified from Barrows, 1948, p. 138]

Location	Time	Elapsed time from preceding station (minutes)	Distance (miles)	Velocity	
				Miles per hour	Feet per second
At dam	11:58 p.m.	-------	------	------	----
City Power House 2	12:03 a.m.	5	1. 5	18. 0	26
Southern California Edison Co. substation	12:38 a.m.	35	7. 5	12. 9	19
Southern California Edison Co. construction camp	1:20 a.m.	42	7. 5	10. 7	16
Fillmore Bridge	2:25 a.m.	65	12. 7	11. 7	17

VAIONT RESERVOIR, ITALY

On October 10, 1963, after 2 weeks of heavy rain, a mass of rock exceeding 240 million cubic meters (8.5 billion cu ft) slid violently into the reservoir of Vaiont Dam, Italy, which then held 135 million cubic meters of water—that is, 4.2 billion cubic feet (Kiersch, 1964). The displaced water swept over both abutments to a height of about 100 meters (without important damage to the actual structure) and claimed nearly 2,600 lives in its disastrous passage downstream. Moving at a speed of about 60 miles per hour, the flood wave was more than 70 meters high when it reached the Piave Valley, 1 mile away, and it struck the village of Longarone head on. Floodwater that continued down the Piave Valley destroyed other villages, and the wave that surged up the valley caused further wreckage and loss of life. Moments later—less than 15 minutes—"the flood waters had receded and all was quiet in the valley." The rueful lesson taught by this tragedy, the worst dam disaster in history, is that the threat of landslide was brought about by several adverse geologic factors, in part augmented by hydrologic effects induced by the impounded water, and that these unfavorable conditions could have been predicted by prior geologic study. Even more tragic, movement of rock was detected 3 weeks before the collapse, but no one anticipated its ultimate magnitude.

FLOODS ASSOCIATED WITH GLACIERS

JÖKULHLAUPS IN ICELAND

The subglacial volcanic eruptions of Iceland are accompanied by floods of large magnitude called glacier bursts (Icelandic jökulhlaup). Similar floods also occur by sudden release of subglacial lakes, which store water generated slowly by volcanic heat. The most active subglacial volcanoes are in southern Iceland, and their intermittent jökulhlaups release enormous floods onto boulder-strewn outwash plains (sandurs) that lie along the coast. (In a lucid display of armchair sleuthing, Warren (1965) attributes an anomalous scabland tract described by Smith (1965) in Wright Dry Valley, Antarctica, to a catastrophic flood produced by an ancient volcanic eruption under thick ice, but scabland on this scale has not yet been found in areas of jökulhlaups in Iceland.)

Discharges and volumes of jökulhlaups have been measured accurately during the last few decades (fig. 25), and records by eyewitnesses extend back several centuries. None of the measured discharges has yet matched the size of some jökulhlaups estimated from early observations. Thus, Grímsvötn, a caldera depression under western Vatnajökull, has discharged at a maximum recorded rate of 50,000 cubic meters per second (1¾ million cfs), but a jökulhlaup caused by the 1918 eruption of Katla, a volcano buried by the Mýrdalsjökull, reached a maximum discharge of at least 100,000 cubic meters per second (3½ million cfs) (Thorarinsson, 1957). The 1918 jökulhlaup from Katla has been estimated as high as from 300,000 to 400,000 cubic meters per second (10–14 million cfs), an amount comparable to the computed peak discharge of the Bonneville Flood.

The large differences in volumes of jökulhlaups shown in figure 25 range from 28 million cubic meters (one billion cu ft) to about 7 billion cubic meters (250 billion cu ft) and are due to various capacities of the subglacial reservoirs. The Grímsvötn caldera is a large depression capable of holding most of the water released during eruptions. It currently fills at the rate of 0.6 cubic kilometers per year, and its recent glacier bursts have been at intervals of 4–6 years (Thorarinsson, 1960, p. 43). Lake Graenalón, a deep basin dammed by ice at the southeast margin of Vatnajökull, also has a large

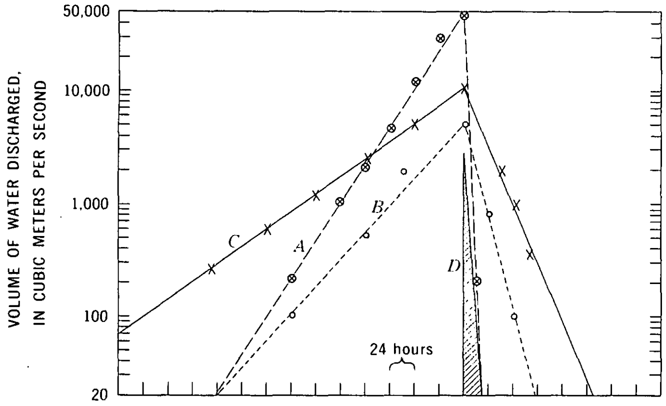


FIGURE 25.—Discharge graph of some glacier bursts recorded in Iceland. (Modified from Thorarinsson, 1957, fig. 2.) *A*, Grímsvötn, March 22–April 1, 1934, total discharge $\sim 7 \times 10^9$ m^3; B, Graenalón, July 23–August 2, 1939, 1.5×10^9 m^3; *C*, Grímsvötn, July 4–22, 1954, 3.5×10^9 m^3; *D*, Katla, June 25, 1955, 28×10^6 m^3.

capacity. The subglacial reservoir of Katla, however, is small (Thorarinsson, 1957).

The different rates of discharge shown in figure 25 are related to constrasting slopes down which the jökullhlaups must descend while forcing a way under the ice. Thus, the slope from the storage area to the outlet is 1:38 for Grímsvötn, 1:40 for Graenalón, and 1:16 for Katla. Discharge rates for Grímsvötn and Graenalón, which have similar slopes, are therefore nearly alike; whereas the maximum discharge for Katla, which has a steeper slope, is reached very quickly, within an hour.

Jökulhlaups carry rocks of extraordinary size far onto the sandur plains. Published photographs of the sandurs show a gravelly plain strewn with subrounded boulders several feet in diameter (Thorarinsson, 1958, figs. 5, 13). Blocks from Öraefajökull, southern Vatnajökull, which were carried by a jökulhlaup in 1362, project 4–5 meters above a sandur plain 4 kilometers from the point of discharge (Thorarinsson, 1958, p. 34). The largest piece found in this area has a base measuring 50 square meters and weighs more than 5,000 tons. Thorarinsson's map (1958, pl. 1) shows that the gradient on the plain at this place is about 7 percent. A tuff-breccia block of about 400 cubic meters lying on the Mýrdalssandur 14 kilometers from the glacier margin was washed out by the 1918 jökulhlaup from Katla (Thorarinsson, 1960, p. 43).

Sedimentation on a sandur plain in the Hornafjördur area at the east margin of Vatnajökull has been studied in some detail by Hjulström (1952). Near the glacier margin, where the gradient is 13–14 percent, the sediment consists of poorly sorted rounded boulders as much as 2 feet in diameter. Large pieces are found as far as 3 kilometers from the glacier, where the gradient is reduced to 4–5 percent, although the average size of particles decreases rapidly from head to toe. The particle size also diminishes from the surface downward. Hjulström attributes the wide range of sizes partly to deposition by jökulhlaups and describes the sandur plain as a "supra-aquatic delta" in which material is deposited simultaneously everywhere on the plain (fig. 26). From a quantitative study of discharge, however, Krigström (1962, p. 341–342) concludes that the Hoffellssandur to the east of Vatnajökull is never completely submerged, even during glacier bursts. Some idea of the rapidity of accumulation of such sandur deposits is given by Thorarinsson (1958, p. 26) from an eyewitness account of the 1362 eruption of Öraefajökull: a glacier burst carried into the sea "such quantities of rocks, gravel and mud as to form a sandur plain where there had previously been thirty fathoms of water." Such descriptions evoke an image of the Melon Gravel.

VARIOUS ICE-DAMMED LAKES

Of the many glacier-dammed lakes that occasionally discharge catastrophic floods (Hutchinson, 1957, p. 50–56), the Märjelensee, a lake dammed by a branch of the Aletsch Glacier in Switzerland, is a classic example. In July 1872, this lake catastrophically released 10.7 million cubic meters of water; in July 1892, 7.5 million; and in July 1913, 3.1 million (that is, 380 million cu ft, 260 million, and 110 million, respectively).. These floods transported great amounts of sediment (Lütschg, 1915).

In western North America the more than 50 ice-dammed lakes in Alaska and British Columbia are remote and difficult to study, but catastrophic outbursts from some of them are known to have had disastrous consequences for life and property. Marcus (1960) reviews current knowledge of these glacial floods and gives a detailed history of one ice-dammed lake, Tulsequah, which lies on the east edge of the Juneau Icefield. Almost annually, during at least the past 50 years, Lake Tulsequah has drained suddenly by failure of its

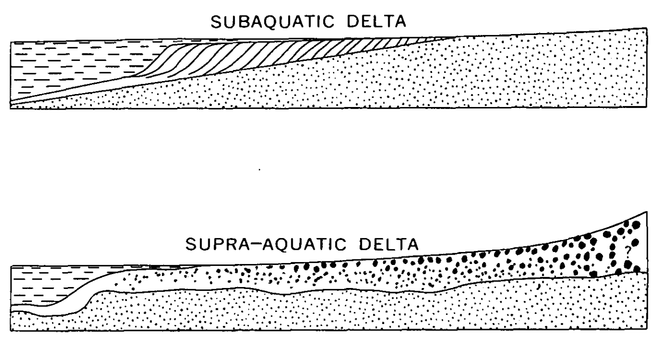


FIGURE 26.—Section of a supra-aquatic delta of sandur type compared with section of ordinary subaquatic delta. (Reproduced from Hjulström, 1952, fig. 8.)

glacier dam. In 1958, the lake released 230 million cubic meters of water (8 billion cu ft), most of it in 2 days, which discharged at a maximum rate of more than 1,500 m³ per second (55,000 cfs). The periodic glacial bursts from Lake Tulsequah are trivial in comparison with the Bonneville Flood, but they are nonetheless of grave concern to the imperiled residents downstream.

SUMMARY OF HISTORIC FLOODS

The foregoing examples of catastrophic floods dramatically illustrate the havoc caused by large volumes of water released suddenly. Some of these historic floods may have discharged for short periods at rates comparable to the sustained discharge of the Bonneville Flood, and all of them attained high velocities. They therefore transported debris of impressive size and quantity. None of them, however, was nearly as large in volume as the Bonneville Flood. The largest, the 1934 jökulhlaup from Grímsvötn in Iceland (volume about 1.7 cubic miles) was less than one two-hundredth of the possible volume of the Bonneville Flood; namely, 380 cubic miles. These floods undoubtedly would have caused spectacular erosion if the available volumes of floodwater had been larger and if the floods had correspondingly lasted longer.

These historic floods also provide obvious lessons for evaluating the hydraulic behavior of large volumes of rapidly moving water. Such information is of value to engineers. Conversely, the hydraulic behavior of the Bonneville Flood, as displayed by its geologic record, tells much about conditions required to produce catastrophic geologic effects of lesser magnitude. The sandur streams of Iceland, for instance, flow in a braided network among bars that resemble diminutive versions of bars of Melon Gravel. The discharge and water depth inferred for the Bonneville Flood, if appropriately reduced in scale, therefore can give some idea about floods responsible for the sandur plains. Lastly, the Bonneville Flood caused substantial erosion, notably where floodwater that debouched over jointed rimrock produced turbulent eddies. Such erosion, and the resulting piles of debris downstream, can be anticipated wherever floodwater is deep enough to submerge large irregularities in the flood path.

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