Large Prehistoric Flood Along Paulina Creek, Newberry Volcano, Oregon

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ABSTRACT

Paulina Creek begins as outflow from Paulina Lake, one of two lakes in Newberry Caldera, and flows down the west flank of Newberry Volcano. Thirteen miles to the west, Paulina Creek joins the Little Deschutes River. Average annual discharge of Paulina Creek is 18 ft^3/s (0.51 m^3/s).

In late Holocene time, a flood poured down the channel of Paulina Creek, which swept away Mazama ash, left trains of boulders, and created or altered many waterfalls, some of which are now dry.

Along the southwest and east shores of Paulina Lake in Newberry Crater is a wave-cut terrace several feet above the current natural lake level. Sudden failure of the outlet sill of Paulina Lake caused lake level to drop 5 to 8 feet (1.5 to 2.4 m) and lake water to flood the channel of Paulina Creek.

Using waterfall dimensions in the equation for a free overfall weir, initial discharge is estimated to be between 4000 and 10,000 ft^3/s (110 to 280 m^3/s). In 6.5 hours, discharge was 50 percent of initial discharge and in 33 hours it was 10 percent.

Based on radiocarbon dates, the flood occurred between 1730 and 4860 calendar years B.P.

An older and higher wave-cut terrace suggests that the Paulina Creek channel was inundated by an earlier flood. The occurrence of episodic floods may have resulted from the upstream migration of waterfalls that reached the sill of the lake.

INTRODUCTION

Abundant evidence suggests that a large volume of water was rapidly discharged from Paulina Lake in Newberry Caldera, flowed westward down the channel of Paulina Creek, and entered the Little Deschutes River (Jensen and Chitwood, 1996). Concern over a future flood that could affect homes, businesses, and transportation systems has been raised (Sherrod and others, 1997). We examine the probable cause of this flood as well as its magnitude, duration, and timing.

Newberry Volcano is a large shield-shaped volcano of Quaternary age, which lies about 35 miles (56 km) east of the Cascade Range (Fig. 1). It covers about 500 mi^2 (1300 km^2) and has a summit caldera of 17 mi^2 (44 km^2). Basaltic-andesite lavas of late Pleistocene and Holocene age cover the north and south flanks, and tephras and sediments cover the west and northeast flanks. Many of the lavas extend well beyond the edifice of Newberry. Newberry caldera formed as a composite of smaller, overlapping calderas during large, violent andesitic to rhyolitic eruptions in the late Pleistocene. Following these eruptions, the caldera has been filling with deposits from smaller, intracaldera eruptions and wall collapses. Today, the caldera floor is largely comprised of obsidian flows, silicic air-fall and ash-flow deposits, palagonitic tuff rings, and basaltic andesite lava. Most of these are Holocene in age. During the late Pleistocene, Newberry caldera probably held a large lake much like Crater Lake to the south. But by the early Holocene, volcanic deposits had partitioned the caldera into two basins now occupied by Paulina Lake and East Lake.

Newberry volcano lies in the rain shadow of the Cascade Range and receives an average annual precipitation of about 30 inches (76 cm) in its caldera and upper flanks (Morgan and others, 1997). Surface water on the volcano is limited to East Lake, Paulina Lake, and ephemeral Lost Lake, which are within the caldera, and to Paulina Creek, which flows down Newberry's west flank. East Lake lies within a closed basin and has no surface outlet. Its surface is about 40 ft (12 m) higher than that of Paulina Lake (Johnson and others, 1985).

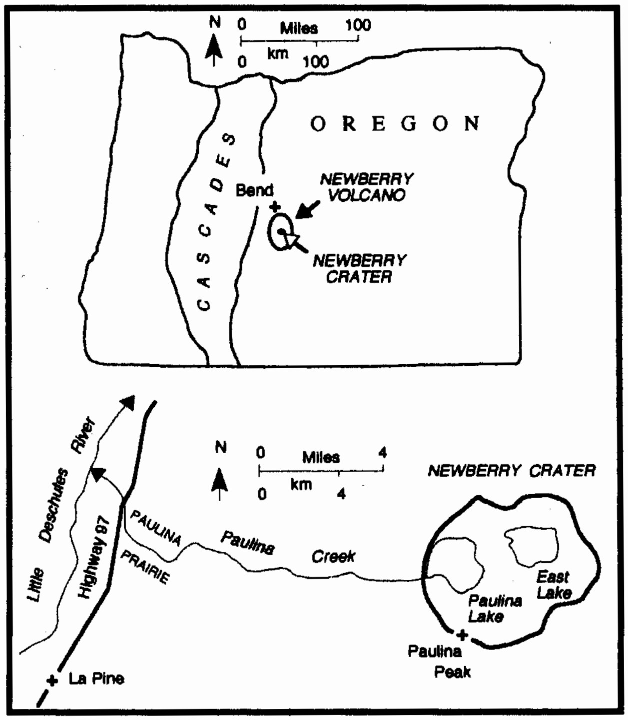

Figure 1. Location maps of Newberry Volcano and Paulina Creek.

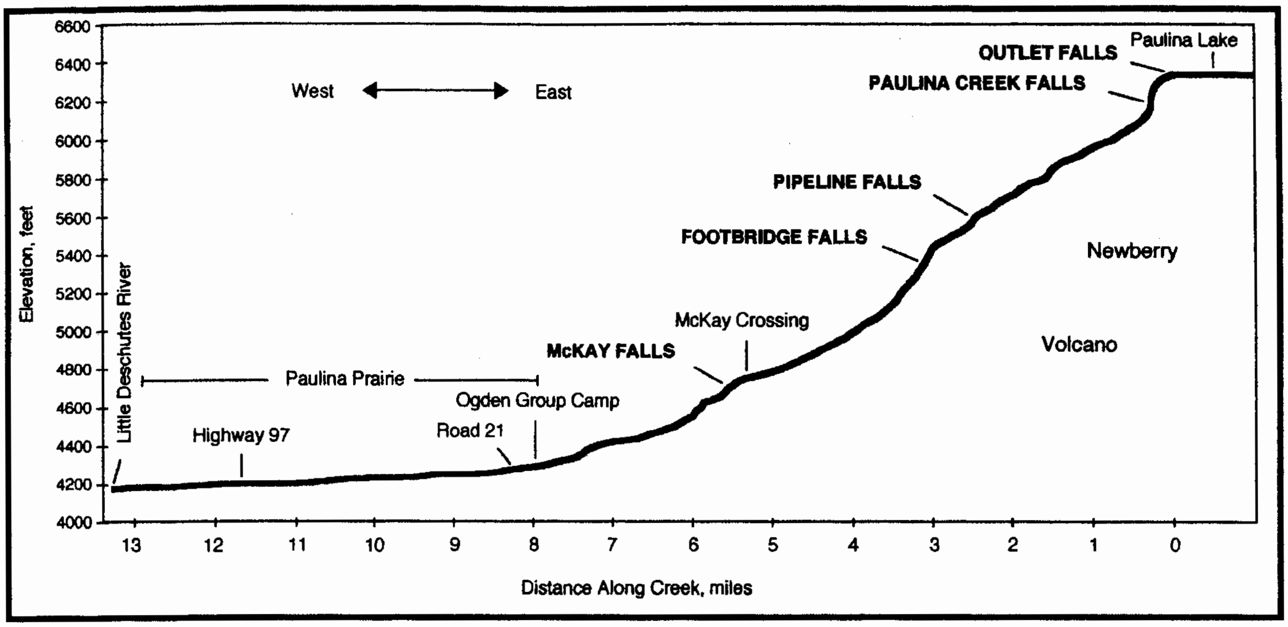

Figure 2. Profile of Paulina Creek showing waterfalls and other features.

PAULINA CREEK

Paulina Creek begins as outflow from Paulina Lake at elevation 6332 ft (1930.5 m) and discharges into the Little Deschutes River 13.3 river miles (21.4 km) to the west at elevation 4177 ft (1273 m) (Fig. 2). For the first 8 miles, Paulina Creek's gradient averages 2.5° (range 1° to 7°). The creek has eroded 30-100 ft (9 to 30 m) into andesitic ash-flow and air-fall deposits (Qat), basaltic andesite (Qba), rhyolite (Qer and Qrd), and unconsolidated sediments (Qs) (MacLeod and others, 1995).

Beginning at river mile 8 at Ogden Group Camp (elevation 4300 ft, 1311 m), the creek flows onto the upper end of Paulina Prairie, a paleo-floodplain with a gradient of 0.25° that extends to the Little Deschutes River. Along its 5-mile (8 km) length, Paulina Prairie broadens to 2500 ft (760 m).

Paulina Creek cascades over several free-falling waterfalls. The largest is Paulina Creek Falls, a scenic double falls, located only 1250 ft (380 m) downstream from the outlet of Paulina Lake. This waterfall and four others are useful for estimating peak discharge during the flood. Most waterfalls have no names, so we have informally named them Outlet Falls (for falls immediately below the outlet of Paulina Lake), Pipeline Falls (for an old wood-stave pipeline nearby), Footbridge Falls (for a well-used pedestrian and horse bridge upstream), and McKay Falls (for McKay Crossing, a well-known vehicle bridge upstream). All waterfalls occur in basaltic andesite (Qba) except Paulina Creek Falls, which occurs in andesitic tuff (Qat) (MacLeod and others, 1995).

The mean annual discharge of Paulina Creek is 18 ft^3/s (0.51 m^3/s) with minor additions and losses along the first 8 miles (Morgan and others, 1997). The range of mean monthly discharge was 4 to 36 ft^3/s, which is largely due to storage and releases for irrigation and to variations in precipitation.

PAULINA LAKE

Paulina Lake fills the western of two basins in Newberry caldera with 250,000 ac-ft (308 hm^3) of water (Johnson and others, 1985). The surface area is 1531 ac (620 ha) and maximum depth is 250 ft (76.2 m). The lake is roughly circular with a diameter of approximately 9200 ft (2800 m). From 1899 to the present, a small irrigation dam constructed at the lake's outlet has controlled lake level (Fig. 3). Surface elevation varies from about 6331 to 6334 ft (1930-1931 m). The elevation of the andesitic tuff sill that controlled lake level before 1899 is about 6328 ft (1929 m).

Figure 3. Outlet of Paulina Lake with Outlet Falls in foreground. A concrete dam under the bridge allows storage of irrigation water. The dam is constructed on the andesitic tuff sill that controls the natural level of the lake.

EVIDENCE FOR A FLOOD

During the spring of 1994 while investigating archaeological sites with Alex Bourdeau, an archaeologist, Chitwood discovered that Mazama ash was completely missing from the floodplain of Paulina Creek at Ogden Group Camp. Chitwood expected to see about 24 inches (60 cm) of the ash covering the floodplain as it does the adjacent land (MacLeod and Sherrod, 1992). Shortly afterwards, Chitwood and Jensen walked the 8-mile section of Paulina Creek from Ogden Group Camp to Paulina Lake and observed that Mazama ash was missing from the entire channel floor. The Mazama ash is a widespread deposit of dacitic airfall tephra from the eruption of Mount Mazama (Crater Lake) approximately 7630 calendar years ago B.P. (Bacon, 1983). The most likely explanation for the missing Mazama ash was that a flood had swept it away.

We observed other features in the channel of Paulina Creek that could only have been formed during a far greater discharge than that of the present. These include boulder trains, gravel bars, abandoned waterfalls and channels, and bedrock erosional features such as potholes, flute marks, polished rock with facets, and various erosional pits and grooves (Baker, 1988).

At many locations in the Paulina Creek channel, boulder trains and gravel bars are found in wider sections immediately below narrow sections (Fig. 4). This is particularly notable at Ogden Group Camp and below McKay Crossing where cobbles and boulders up to 35 inches (90 cm) in diameter form broad, low, longitudinal ridges flanked by gravel bars on one side and a shallow channel on the other.

Abandoned waterfalls and channels are well-developed in the basaltic andesite at Footbridge Falls (Fig. 5). Here, the channel is unusually wide, 180 ft (55 m), and divides into two distinct channels each headed by a waterfall. The channels converge about 500 ft (150 m) downstream. Paulina Creek cascades over a limited section of the southern waterfall. This is in striking contrast to the dry and abandoned northern waterfall. A 12-inch (30-cm) diameter pothole completely penetrates the overhanging basalt sill of the dry waterfall. The nearly horizontal surface of a long penninsula separating the channels is devoid of Mazama ash and displays several bedrock erosional features. During the event that swept away the Mazama ash, the entire penninsula and its two flanking waterfalls were evidently completely flooded.

Figure 4. Boulder train at Ogden Group Camp. This site is located 8.0 miles (13 km) downstream from the Paulina Lake outlet.

A substantial amount of sand and gravel was deposited in the 6000 ft (1830 m) of Paulina Prairie, which includes Ogden Group Camp. The average maximum particle size decreases linearly from 25 inches (63 cm) at 1000 feet (300 m) from the head of the prairie to 2 inches (5 cm) at 5100 feet (1550 m). Width of the prairie along this stretch varies from 600 to 900 feet (183 to 274 m). At 8000 feet (2440 m), the prairie widens to 2500 feet (760 m). Sand and fine gravel are confined to the central part of the prairie, and about 25 inches (63 cm) of Mazama ash flank the sand and fine gravel.

MAGNITUDE

The magnitude of the flood can be estimated by matching the geometry of an appropriate standard weir with that of certain Paulina Creek waterfalls (Jim O'Connor, pers. comm.). Using the weir formula, discharge can be calculated using measurements of the waterfalls. The estimate will be crude because the irregular geometry of each waterfall does not precisely match the simple geometry of the weir.

The weir that most closely matches the geometry of the waterfall profiles is the free overfall, a type of broad-crested weir (Morris, 1963, p. 157). In this case, water flowing in a low gradient channel with a

Figure 5. Footbridge Falls. The falls are located 3.1 miles (5.0 km) downstream from the Paulina Lake outlet. Discharge is approximately 20 ft^3/s (0.57 m^3/s). Out of view to the left is a dry falls of similar size, potholes, and polished rock with facets.

rectangular cross section pours over a brink into air (Fig. 6). As water approaches the brink, its depth decreases to approximately 0.7 that of the upstream depth (measurement of the upstream depth must be taken at a distance of at least 5 times the brink depth).

The standard formula for a free overfall weir is

$$Q = C * W * D{}^\wedge 1.5 \qquad \text{(eq. 1)}$$

Where Q = discharge, $\mathrm{ft^3/s}$
C = a constant, 9.4
W = width of weir, ft
D = depth of water at brink, ft

We estimated the depth of floodwater at each waterfall by using one or more of four approaches: (1) the highest elevation where Mazama ash was removed, (2) the highest elevation of boulder trains and gravel bars immediately upstream, (3) the change in slope along the channel edges due to erosion assumed to have occurred during the flood, and (4) the immediate upstream channel geometry and its influence on where water is likely to flow.

Since it is virtually impossible to determine precise paleo-water levels at the waterfalls, we estimated a range of probable depths.

Waterfall	Minimum Depth (ft, m)		Maximum Depth (ft, m)	
Outlet	5	1.5	8	2.4
Paulina Creek	7	2.1	13	4.0
Pipeline	5	1.5	14	4.3
Footbridge	5	1.5	12	3.7
McKay	8	2.4	12	3.7

To estimate discharge of Paulina Creek during the flood, a discharge curve was calculated for each waterfall. Figure 7 shows profiles measured along the brinks of five selected waterfalls. Note that none have a simple rectangular cross section during discharge. However, the cross section of Outlet Falls comes closest. To partially account for these irregular profiles, discharge calculations were made for small rectangular areas spaced every foot (W = 1) along the profile (Fig. 8). The top of each rectangle was fixed at the elevation of an assumed horizontal water level above the brink. The depth (D) and width (W) of each rectangle were entered into the weir formula; discharge was calculated; and the sum of all discharges through all rectangles was taken to be the discharge of the waterfall.

For discharge at water level 1:

$$QD1 = Qa1 + Qb1 + Qc1 \ldots Qx \qquad \text{(eq. 2)}$$

For discharge at water level 2:

$$QD2 = Qa2 + Qb2 + Qc2 \ldots Qx2, \text{etc.} \qquad \text{(eq. 3)}$$

A discharge curve based on a regression of calculated waterfall discharges for several water levels (QD1, QD2, etc.) was found to be a power function with an r squared correlation of 0.99 to 1.00 for each waterfall.

Waterfall	Discharge ($\mathrm{ft^3/s}$)	
Outlet	$Q = 199 * D^{1.88}$	(eq. 4)
Paulina Creek	$Q = 229 * D^{2.19}$	(eq. 5)
Pipeline	$Q = 29.0 * D^{2.63}$	(eq. 6)
Footbridge	$Q = 189 * D^{2.27}$	(eq. 7)
McKay	$Q = 39.9 * D^{2.49}$	(eq. 8)

Figure 9 shows estimates of minimum water depth plotted on the discharge curves. Most estimates of maximum water depth seem unreasonably large and are not plotted. The estimated range of water depth at Outlet Falls is constrained by two deposits of Mazama ash. Maximum depth did not exceed 8 feet (2.4 m). A higher water level would have removed a deposit of undisturbed Mazama ash on the south side of channel at Outlet Falls. Minimum depth was about 5 feet (1.5 m). Below this water level, all undisturbed Mazama ash at the outlet has been removed. From the discharge curve of Outlet Falls, the range of water depths correspond to a range of probable discharges from about 4000 to 10,000 $\mathrm{ft^3/s}$ (110 to 280 $\mathrm{m^3/s}$). This range is consistent with calculated discharge at the other waterfalls except for Paulina Creek Falls, which is too high.

Another significant constraint on the depth of floodwater at Outlet Falls is based on a nearby lakeside archaeological excavations. Undisturbed Mazama ash is found only in excavations ≥5 feet (≥1.5 m) above the natural outlet sill of Paulina Lake. This suggests that at the initiation of the flood either lake level was about 5 feet (≥1.5 m) above the present outlet sill or lake level temporarily rose an additional few feet without noticeably eroding the Mazama ash. Either way, the case for water depth in the 5 to 8 foot (1.5 to 2.4 m) range is strengthened.

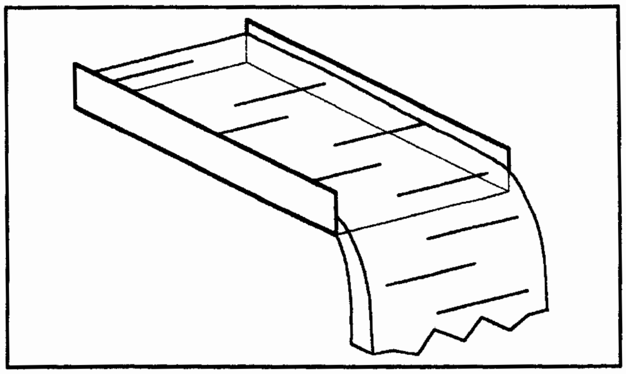

Figure 6. Ideal configuration of a free overfall weir. Discharge is calculated from the width and depth of water at the brink.

DURATION

The duration of the flood can be estimated if it is assumed that the flood resulted from the sudden failure of the outlet sill of Paulina Lake. This would be equivalent to the failure of a 5- to 8-foot-high (1.5 to 2.4 m) dam. The duration was estimated based on an iterative approach in which we calculated the time necessary for an incremental volume of Paulina Lake to flow over the sill of the outlet. As water depth at the failed dam decreases, the time interval for each successive incremental volume to flow out of the lake increases.

To estimate duration, discharge at Outlet Falls was calculated for depth intervals of 0.0l feet (3 mm) (e.g., 8.00, 7.99, 7.98, etc.) using equation 4 above. Each depth interval was associated with a small volume of the lake. The time interval necessary for each of these volumes to discharge was calculated. Cumulative time and discharge were tabulated and graphed (Fig. 10).

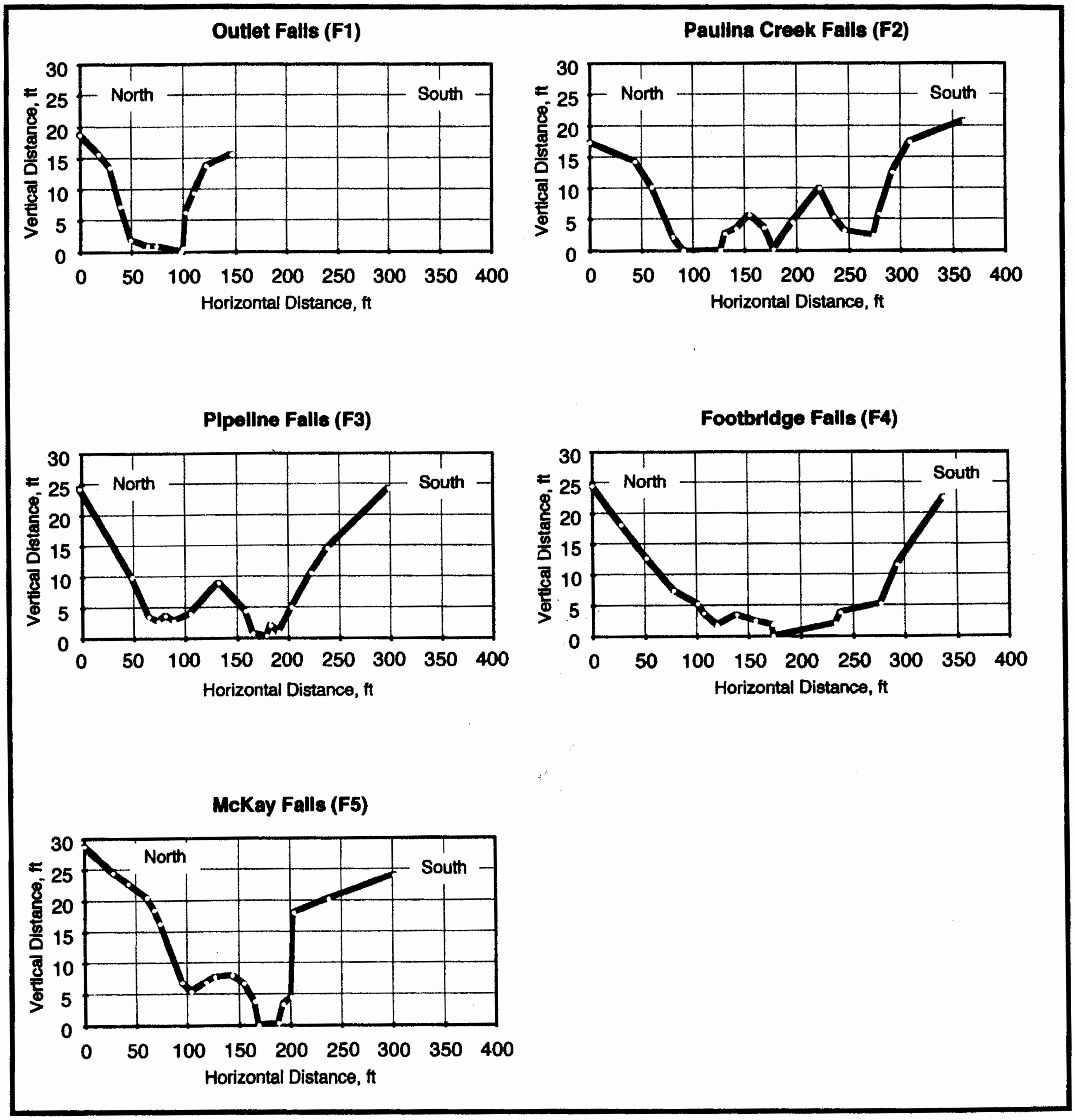

Figure 7. Profiles along the brink of selected waterfalls. Note that Outlet Falls most closely approximates a rectangular cross section, which makes it particularly useful for estimating flood discharge.

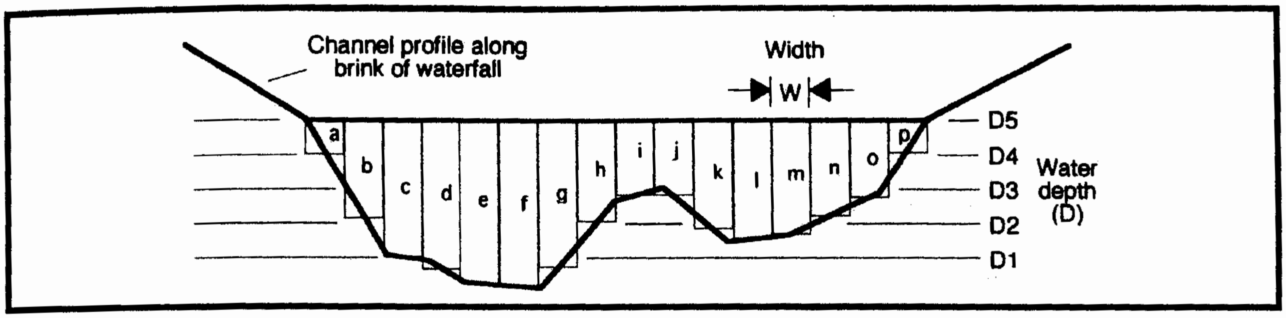

Figure 8. Method of calculating a waterfall discharge curve. Discharge at a waterfall is the sum of discharges calculated for each rectangle for a given water depth. A curve is fitted to the discharges calculated for several water depths.

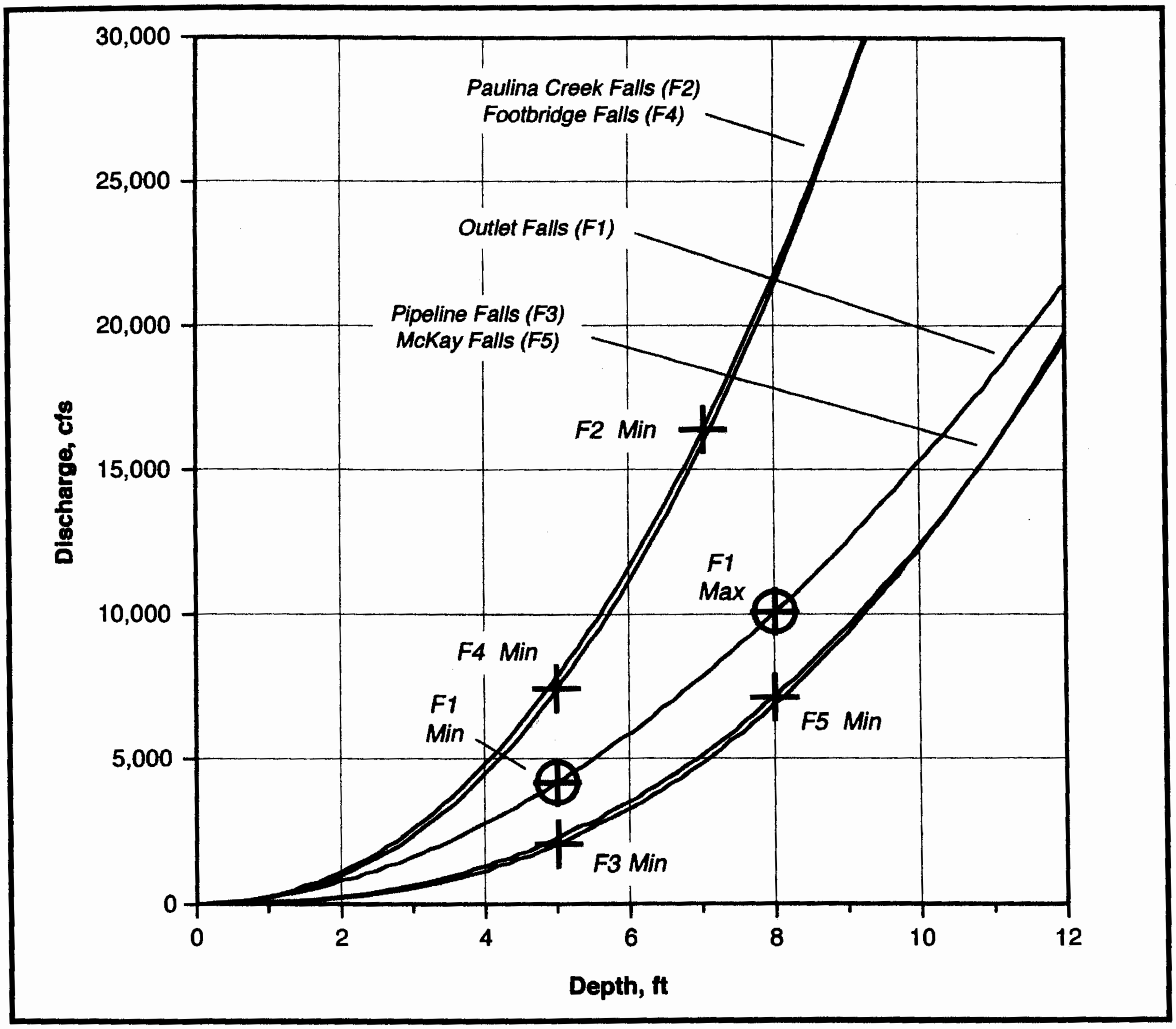

Figure 9. Discharge curves for selected waterfalls along Paulina Creek (see text for explanation). Estimates of minimum water depth are plotted (+). These are based on the position of flood-related erosional and depositional features observed at each waterfall. Conditions at Outlet Falls (F1) offer the best constraints on the range of probable discharge. For this waterfall, both a minimum and maximum water depth are shown (circled +). Maximum estimated depth for all other waterfalls is 12 feet or more and are not plotted. The flood discharge most likely falls in the middle to upper part of the range of 4,000 to 10,000 ft³/s (110 to 280 m³/s).

	Discharge (ft^3/s, m^3/s)			
Time (hr)	5-Foot Dam		8-Foot Dam	
0	4100	116	9920	281
4	3020	86	6320	179
8	2300	65	4360	124
12	1810	51	3700	105
16	1460	41	2510	71
20	1200	34	1880	53
24	1000	28	1510	43

Various depth intervals were initially used to calculate discharge and time. A smaller depth interval provides greater precision. For a duration of 48 hours, the depth interval of 0.01 feet yielded a discharge that was 4 percent less than the result for 0.1 feet. This is far more precise than field constraints of water depth and probable changes of outlet geometry during failure.

AGE

The timing of the flood is constrained by the age of four deposits and by a rock oven found at an archaeological site.

Mazama ash.

The flood completely removed Mazama ash from the upper 9 miles of the floor of the Paulina Creek. The radiocarbon age of the Mazama ash is 6845 years B.P. (Bacon, 1983) or 7630 calendar years B.P. (calculated from Stuiver and Reimer, 1993).

Interlake Obsidian Flow.

When the outlet sill of Paulina Lake failed, the level of Paulina Lake dropped by several feet. Near the northeast corner of the lake, on the north and south sides of the Interlake Obsidian Flow, the terrace is covered by rounded obsidian gravels and obsidian gravel bars. There is no erosional terrace cut into the flow but there are scattered obsidian gravel bars along the northern edge of the flow (Jensen and Chitwood, this guidebook). At the northeast corner of the lake, this terrace level is marked on the Interlake Obsidian Flow by small gravel bars containing obsidian from the Interlake Obsidian Flow. A hydration rind date of 6700 years ago was determined by Friedman (1977) for the Interlake Obsidian Flow. But this age is too young based on stratigraphic position and bracketing radiocarbon dates. The age of the Interlake Obsidian Flow lies between 6910 and 7270 calendar years B.P., based on radiocarbon dates (Jensen, 2000). The flood occurred some time after this in order for waves to form the obsidian gravel bars.

Terrace deposits.

Terrace deposits of unconsolidated and well-cemented gravel and sand are found along the east and south shores of Paulina Lake. The gravel and sand were deposited when waves of the lake were actively developing the terrace and terrace deposits. Wood within the deposit was radiocarbon dated at 4860 calendar years B.P. MacLeod and others (1995) believed that the terrace were overlain by Mazama ash and that the date was too young. It is now known that the terrace is not overlain by Mazama ash. The

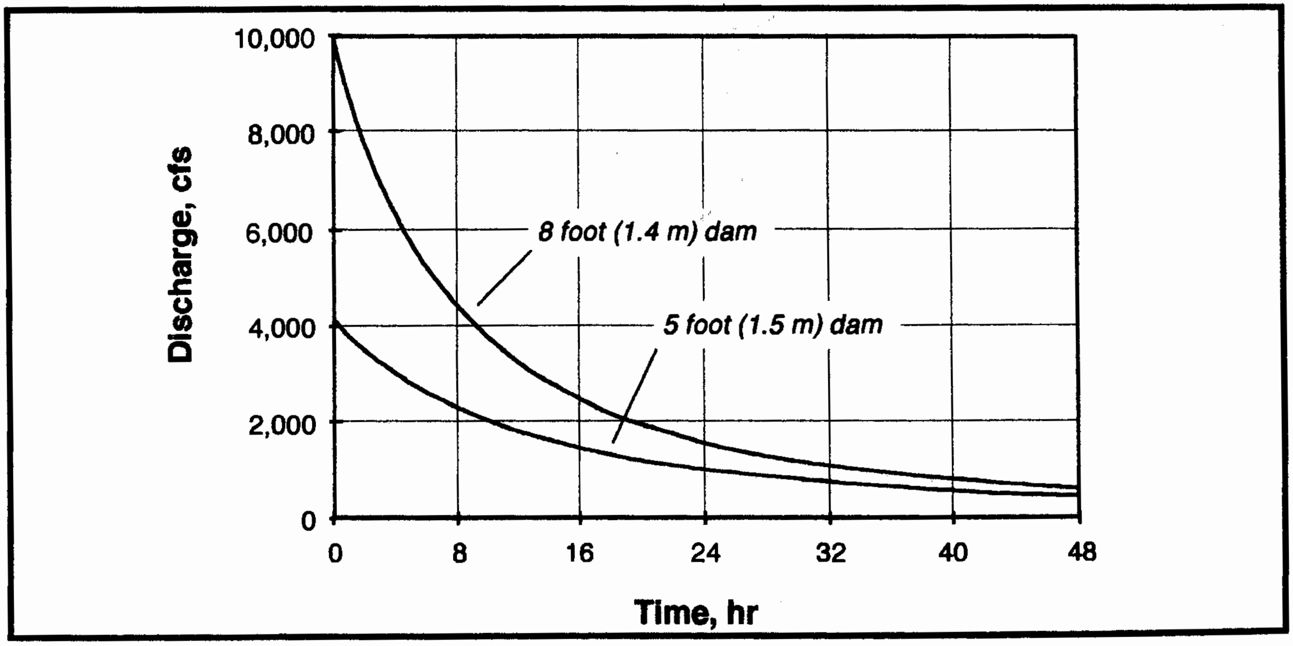

Figure 10. Discharge and duration of a flood. If a dam at Outlet Falls should suddenly fail, a considerable amount of water would discharge into Paulina Creek and the level of Paulina Lake would fall.

lake retreated from the terrace sometime after this date.

Rock oven.

Archaeologic excavations along Paulina Creek at Ogden Group Camp provide further constraints of the timing of the flood. These excavations were begun immediately after the discovery of the flood and were sited to provide information about the flood (Bourdeau, 1994, 1995). One site in particular (Eastgate Site) exposed a rock oven and associated charcoal. The oven was buried within Mazama ash colluvium that accumulated near the bottom of a slope behind a gravel levee. The gravel levee was probably deposited during the flood. Charcoal from the oven was dated at 1730 calendar years B.P. Since the rock oven was located in the lower half of the Mazama ash colluvium, a substantial amount of time may have passed to account for the accumulation of the Mazama ash colluvium under the rock oven.

Paulina Lake ash flow.

The south shore of Paulina Lake is blanketed by a thick deposit from the Paulina Lake ash flow (MacLeod and others, 1995). Toward the eastern end of the south shore the deposit thins rapidly and overlies terrace gravels. If the terrace had still been active and submerged, the thin edge of the ash deposit should have been removed by wave action. The age of this deposit is 1240 calendar years B.P., based on radiocarbon dating (MacLeod and others, 1995). Thus the flood occurred before this date.

In summary, the flood occurred sometime after terrace gravel and sand were deposited 4860 calendar years B.P. This is consistent with the time necessary for terraces and gravel bars to form at the Interlake Obsidian Flow. It is also consistent with a much drier and warmer climate from about 8000 to 5500 years ago (Connolly, 1999, p. 25-26), which may have reduced the level of Paulina Lake to well below its outlet sill for long periods of time. New evidence suggests that lake level was 40 to 60 feet below the current level about 7500 calendar years ago (R. A. Reynolds, this guidebook).

The flood occurred sometime before Native Americans used the rock oven 1730 calendar years B.P. However, if the time necessary for Mazama ash colluvium to accumulate under the rock oven is taken into account, a speculative youngest age of the flood is 2300 calendar years B.P.

CAUSE

Evidence suggests that the outlet sill of Paulina Lake failed in a rapid downcutting event. Sudden failure is recorded in a well-developed wave-cut terrace along the south and east shores of Paulina Lake. The terrace is several feet above present natural lake level. Failure resulted from the upstream migration of a waterfall that reached the lake. The andesitic tuff at the lake's outlet is irregularly stratified with wide-ranging degrees of welding and agglutination, a condition suitable for the formation of waterfalls (Fig. 11). Erosion of weak layers in the tuff is undoubtedly enhanced by freezing and thawing during the harsh winters.

It is unclear whether or not a triggering event led to the sudden failure of the outlet sill. If the sill were on the verge of failure, then any event that substantially raised lake level could hasten failure. This might include displacement of the lake by a large avalanche of rock or snow, rapid emplacement of lava or tephra during an eruption, or by sudden uplift of the lake during movement along a fault. However, no evidence has been found for any of these or other triggering event.

MULTIPLE FLOODS

Two wave-cut terraces are exposed above water level along the south and east shores of Paulina Lake

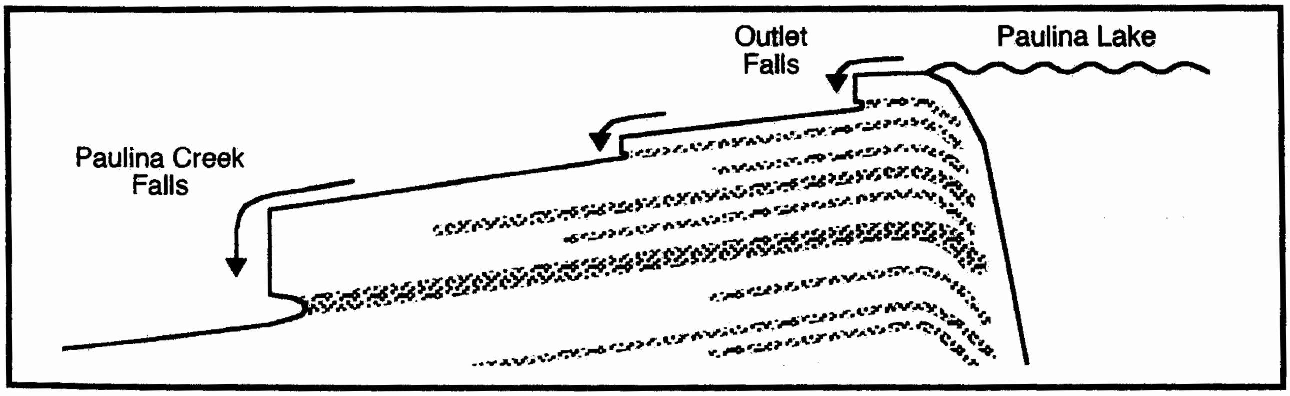

Figure 11. Cross-sectional sketch of caldera rim at outlet of Paulina Lake. Waterfalls develop and migrate upstream as less resistant layers of andesitic tuff (gray lines) erode and allow blocks of welded tuff or agglutinate to break off along vertical fractures. When they arrive at Paulina Lake, failure of the outlet sill results in a flood and lake level drops abruptly.

(Je[illegible] this guidebook). Each rep[illegible] stand of the lake. During eac[illegible] stand, the outlet sill did not significantly erode. Failure of the sill followed the arrival of a waterfall that migrated upstream due to headward erosion. This suggests that two floods have coursed down Paulina Creek. Indeed, headward erosion at Outlet Falls will eventually result in another sill failure and another flood.

We found no direct evidence of multiple floods recorded in the channel of Paulina Creek. However, most erosional and depositional features may be better explained by repeated floods throughout the late Pleistocene and Holocene. Paulina Creek has cut into basaltic andesite tens of feet, created a series of relatively large waterfalls, polished large areas of bedrock, and deposited substantial amounts of sand and gravel in the upper part of Paulina Prairie. It seems unlikely that one flood could produce all these features. Certainly, the scale of these features cannot be explained by the present discharge of Paulina Creek.

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