Late Holocene Uplift of Caldera Floor, Newberry Volcano, Central Oregon.

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ABSTRACT

The caldera of Newberry volcano in central Oregon has been the site of several silicic and mafic eruptions during the past 10,000 yr. Presumably, these eruptions were accompanied by episodes of rising, falling, and tilting of the caldera floor as has been reported at historically active calderas. We report evidence that the floor of the caldera near its center has been uplifted sometime during late Holocene time.

We systematically identified and measured wave-cut terraces along the southwest and east shores of Paulina Lake. These terraces were abandoned when the lake's surface suddenly dropped due to rapid downcutting of the outlet. Following abandonment, terraces were differentially uplifted with a maximum displacement of 14 ft (4.3 m) at Little Crater Campground at the southeast corner of the lake. Along the north shore a terrace may have subsided.

Leveling surveys done in 1931, 1986 and 1994 by the USGS show minor subsidence of the caldera floor.

Uplift is associated with emplacement of magma under a caldera floor and is one of several important indicators of caldera unrest and an impending eruption. At Newberry caldera, MacLeod and Sherrod (1988) suggest that a rhyolitic magma body as much as 3 mi (5 km) in diameter has existed under the eastern half of the caldera throughout the Holocene. All rhyolitic eruptions within the caldera during this time have been confined to this area.

Uplift of the caldera floor may indicate replenishment of a rhyolitic magma chamber centered southeast of Paulina Lake. The uplift suggests a long-term prelude to future rhyolitic eruptions similar to those that have occurred throughout the Holocene (e.g., the Big Obsidian Flow, Newberry Pumice, East Lake Obsidian Flows, and the Central Pumice Cone).

INTRODUCTION

In 1994, we discovered that a large volume of water rapidly drained from Paulina Lake and flooded Paulina Creek in late Holocene time (Chitwood and Jensen, this guidebook). In our search for causes of this flood, we noted that wave-cut terraces lie above present lake level. We concluded that the cause of the flood was failure of the bedrock sill at the outlet of the lake. At failure, lake level suddenly dropped and abandoned the terraces.

A cursory look suggested that the terraces were not at a uniform elevation. A systematic search for terraces was undertaken, and cross sections of terraces were subsequently measured and drawn. We report here the significance and implications of the study of these terraces.

Paulina Lake lies within the summit caldera of Newberry volcano (Fig. 1). The volcano is a large shield-shaped volcano of Quaternary age centered about 24 mi (39 km) south of Bend, Oregon and about 35 mi (56 km) east of the crest of the Cascade Range (MacLeod and others, 1995). It covers about 500 mi² (1300 km²) and the summit caldera covers about 17 mi² (44 km²). 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. Newberry caldera formed as a composite of smaller, overlapping calderas during large, violent andesitic to rhyolitic eruptions in late Pleistocene time. 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 single large lake much like Crater Lake to the south. But by the early Holocene, volcanic deposits had partitioned the

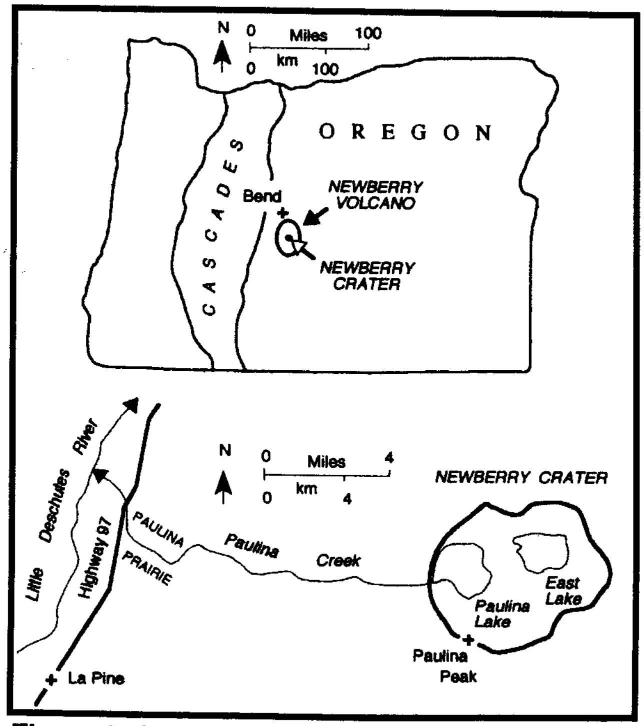


Figure 1. Location map of Newberry Volcano and Paulina Lake.

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 to the Little Deschutes River. 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).

PAULINA LAKE

Paulina Lake has a surface area of 1531 ac (620 ha) and a maximum depth of 250 ft (76 m) (Johnson and others, 1985). It contains about 250,000 ac-ft (308 hm^3) of water and has 6.7 mi (10.8 km) of shoreline.

In 1899, an irrigation dam was constructed about 1000 ft downstream from the lake's natural outlet. The present dam can raise lake level several feet to a spillway elevation of 6332.3 ft. The bedrock channel on which the dam is built has an elevation of 6328 ft, indicating that the lake probably had an elevation of about 6329 ft before the dam was constructed.

Names of selected places and features around Paulina Lake are show in Figure 2.

METHODOLOGY

A systematic search for terraces and terrace deposits included walking and boating along most of the shoreline of Paulina Lake. As terraces were identified and described, cross sections were measured using a cloth tape, hand level, and canoe. Precision of vertical measurements is estimated at ±0.2 ft. Vertical control was based on the surface elevation of Paulina Lake. Since lake level is controlled by a dam, surface elevation was recorded each survey day from a staff gauge located at the dam.

Using the survey points, cross sections were drawn for all sites. A probable lake level that existed before the Paulina Creek flood was visually estimated from each cross section. The estimate was done by selecting the high point of each terrace and estimating a minimum lake level needed to cover the terrace.

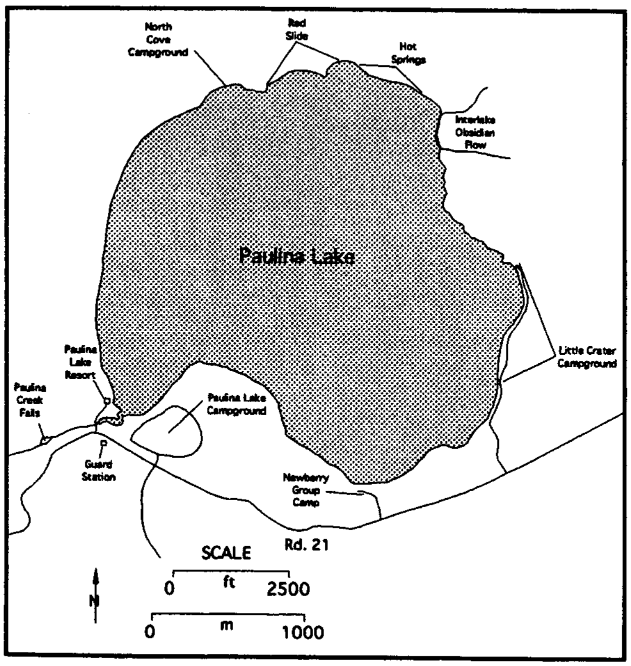


Figure 2. Map of Paulina Lake showing named features along the shore.

WAVE-CUT TERRACES

At Paulina Lake, wave-cut terraces and related terrace deposits of gravel and sand have been recognized (MacLeod and others, 1995). The fact that lake level is lower than the terraces was attributed to downcutting of rock at the outlet of the lake. Our study of the Paulina Creek flood of late Holocene age supports this view (Chitwood and Jensen, this guidebook).

We systematically searched for, identified, and measured terraces around the perimeter of Paulina Lake. Figure 3 shows the general distribution of terraces and the location of 48 measured cross sections. No terraces were observed along the steep western shore. Prevailing winds out of the west drive the most energetic waves onto the eastern shore

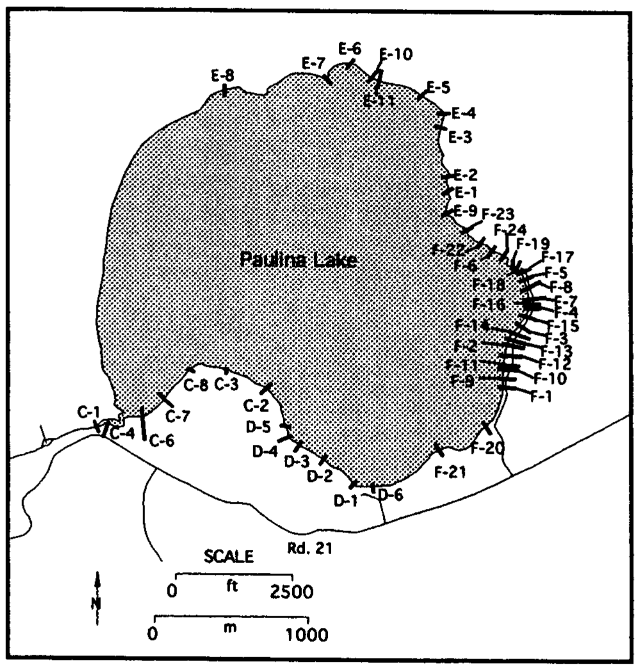


Figure 3. General distribution of wave-cut terraces around the perimeter of Paulina Lake shown by the location of 48 measured cross sections.

where terraces are particularly well-developed and nearly continuous. Figure 4 shows several typical cross sections.

East Shore Terraces

Cross-sections of the east shore from the south end of Little Crater Campground to the north side of the Interlake Obsidian Flow record elevations of a nearly continuous wave-cut terrace with related gravel bars and unconsolidated to cemented (with silica) gravel and sand deposits. Some terrace deposits contain abundant fossils and wood, particularly at the north end of Little Crater Campground. Obsidian gravel bars occur on and north of the Interlake Obsidian Flow, which suggest that terrace development persisted well after the eruption of the Interlake Obsidian Flow. Terrace elevations range from 4 to 10 ft (1.2 to 3.0 m) above normal lake level (elev. 6333 ft) and show a consistent decrease in elevation from south to north (Fig. 5).

Remnants of a higher terrace were found at several locations. This terrace lies 4 to 6 ft (1.2 to 2.7 ft) above the well-developed lower one.

Terrace elevations from cross sections and minimum lake levels needed for terrace development are given in Table 1.

Southwest Shore Terraces

Cross-sections of the southwest shore from the middle of the Newberry Group Camp to the bedrock point east of Paulina Lake Campground show a consistent lake terrace. Terrace elevations range from 4 to 8 ft (1.2 to 2.4 m) above normal lake level (elev. 6333 ft) and generally decrease from south to north, although the trend is not so striking as that of the east shore.

Remnants of a higher terrace were also found at a few locations. This terrace also lies 4 to 6 ft (1.2 to 2.4 m) above the better-developed lower one.

Terrace elevations from cross sections and minimum lake levels needed for terrace development are given in Table 2.

South Shore Terraces

No terraces were found between Little Crater Day Use Area to Newberry Group Camp. Terraces, which surely existed along this margin of the lake, were covered and buried by the Paulina Lake ash flow tephra, which is at least 16 ft (4.9 m) thick based on the exposure at Section F-21. The shoreline was probably moved northward some distance during this eruption.

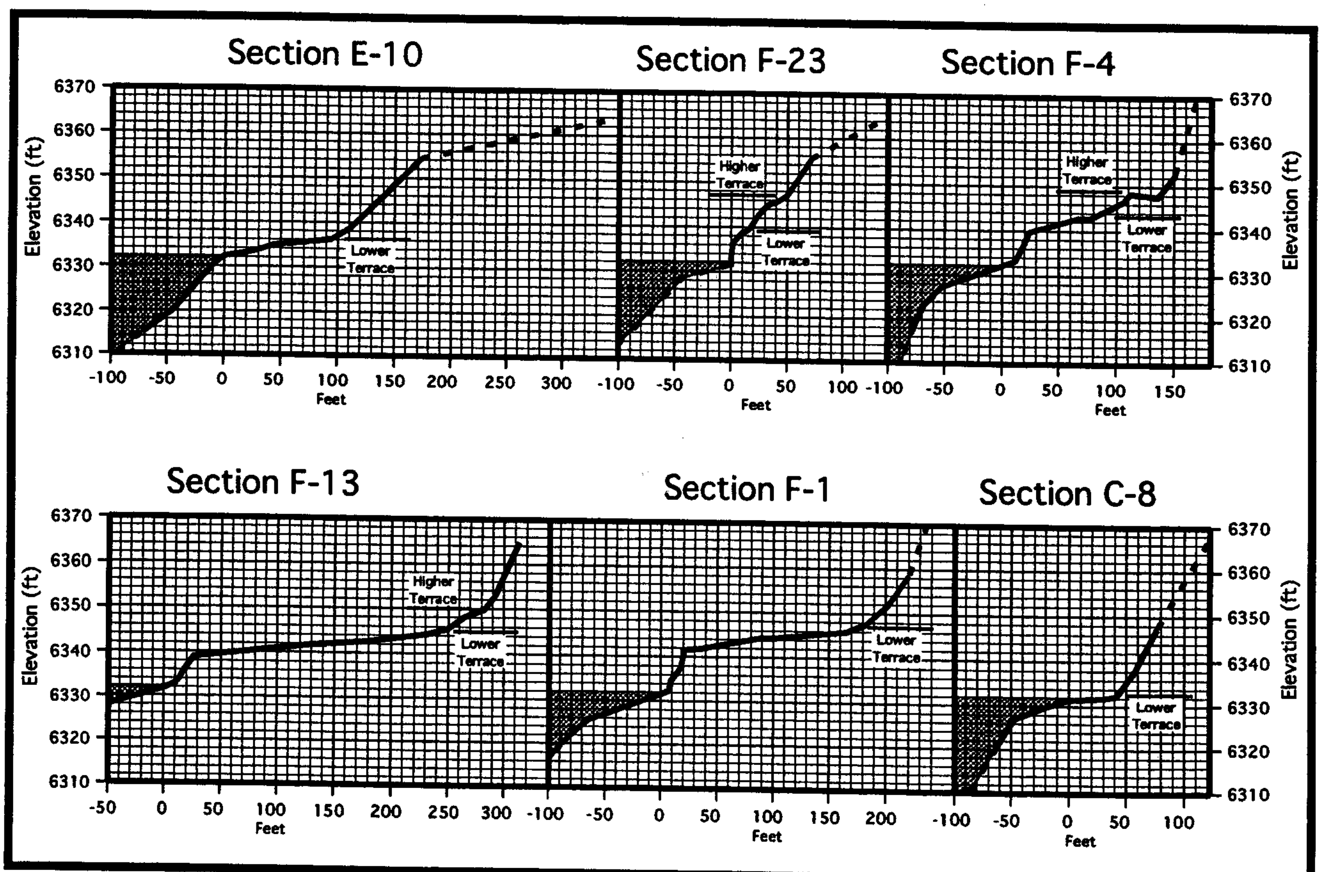


Figure 4. Selected terrace profiles. These typical cross sections are arranged clockwise along the Paulina Lake shore beginning at the north shore (Profile E-10) and ending at the southwest shore (C-8).

Figure 5. Wave-cut terraces along the east shore of Paulina Lake. The terrace on the left is located at the northeast corner of the lake (Profile E-10). The same terrace on the right is 7300 ft (2240 m) to the south at Little Crater Campground (Profile F-9). The elevation difference is due to differential vertical

Table 1. East shore terrace elevations and minimum lake level needed for terrace development (all elevations in ft).

Section Number	Location of Cross-Section	Maximum Elevation of Lower Terrace	Minimum Lake Level	Maximum Elevation of Higher Terrace	Minimum Lake Level
F-1	LCCG campsite #1	6346.8*	6347	--	--
F-9	LCCG campsite #5	6346.3	6346	6351.6	6352
F-10	LCCG campsite #9	6344.5	6345	--	--
F-11	LCCG campsite #10	6345.7	6346	--	--
F-12	LCCG campsite #16	6345.7	6346	6350.3	6350
F-2	LCCG campsite #19	6346.0	6346	6350.0	6350
F-13	LCCG campsite #21	6345.4	6345	6350.0	6350
F-14	LCCG campsite #23	6345.8	6346	--	--
F-3	LCCG campsite #26	6345.5	6346	--	--
F-15	LCCG campsite #29	6344.9	6345	--	--
F-4	LCCG campsite #33	6342.8	6343	6348.3	6348
F-16	LCCG campsite #35	--	--	6347.7	6348
F-7	LCCG campsite #38	--	--	6346.7	6347
F-8	LCCG campsite #44	6341.6	6342	6345.1	6345
F-5	LCCG campsite #46	--	--	6347.7	6348
F-17	LCCG campsite #48	--	--	6347.7	6348
F-18	Trailhead parking	6341.5	6342	--	--
F-19	Along trail-N of LCCG	6341.3	6341	--	--
F-24	Along (757) trail-N of LCCG	6340.7	6341	6345.8	6346
F-6	Along trail-N of LCCG	6340.3	6340	--	--
F-22	Along trail-N of LCCG	6339.1	6340	6345.1	6346
F-23	Along (758) trail-N of LCCG	6339.4	6340	6346.9	6347
E-9	Western most point	6339.3	6340	--	--
E-1	Along trail-S of ILOF	6338.0	6338	--	--
E-2	Along trail-S edge of ILOF	6340.0**	6339	--	--
E-3	Along trail-bar on ILOF ***	6338.4	6338	--	--
E-4	Along trail-bar N of ILOF ***	6338.3	6338	--	--
E-5	Trail north of ILOF	6335.9	6336	--	--
E-11	Trail north of ILOF	6336.0	6336	--	--
E-10	Trail north of ILOF	6336.1	6336	--	--

LCCG = Little Crater Campground. ILOF = Interlake Obsidian Flow.
* After removing 1 ft of Paulina ash-flow deposit
** May not be representative of terrace level; highest adjacent cross-section point is 6338.6 ft.
***Gravel bars on and north of the Interlake Obsidian Flow are made up of obsidian cobbles from the flow

Table 2. Southwest shore terrace elevations and minimum lake level needed for terrace development (all elevations in ft).

Section Number	Location of Cross-Section	Maximum Elevation of Lower Terrace	Minimum Lake Level	Maximum Elevation of Higher Terrace	Minimum Lake Level
D-6	East end Area B in NGC	--	--	6344.9	6345
D-1	Along trail-N of NGC	--	--	6342.5	6343
D-2	Along trail	6339.3	6339	6343.3	6343
D-3	Along trail	--	--	6341.1	6341
D-4	Along trail	--	--	6345.1	6345
D-5	Along trail	6337.5	6338	6342.1	6342
C-2	Along trail	6336.5	6337	6339.6	6340
C-3	Along trail-bedrock point	6334.2	6334	--	--
C-8	Along trail	6332.5	6333	--	--
C-7	PLCG campsite #35	6332.6	6333	--	--
C-6	PLCG campsite #4	6333.0	6333	--	--

NGC = Newberry Group Camp. PLCG = Paulina Lake Campground.

North and West Shore Terraces

Along the west and north shores from north of Section E-10 to Paulina Lake Lodge, no terraces were found. The slopes behind these shores are generally steep and high. Erosion and slope ravel may have removed evidence of a terrace. Or subsidence or downfaulting of this part of the lake basin may have submerged any terrace.

Other Terraces

At Red Slide point, two wave-cut surfaces occur below lake level. They were cut into the basalt flow which makes up the point. The higher surface is at an elevation of about 6329 ft (4 ft, 1.2 m, below current lake level). The lower surface is at an elevation of 6323 ft (10 ft, 3.0 m, below current lake level). If these surfaces are wave-cut terraces that correspond to those along the east shore, then this part of the lake basin may have subsided or been downfaulted.

From north of Section E-10 to North Cove Campground, four cross-sections show a consistent break in slope well above current lake level (about 17 ft, 5.2 m). It is unclear what this represents.

See Table 3 for elevation breaks in cross sections along the north shore.

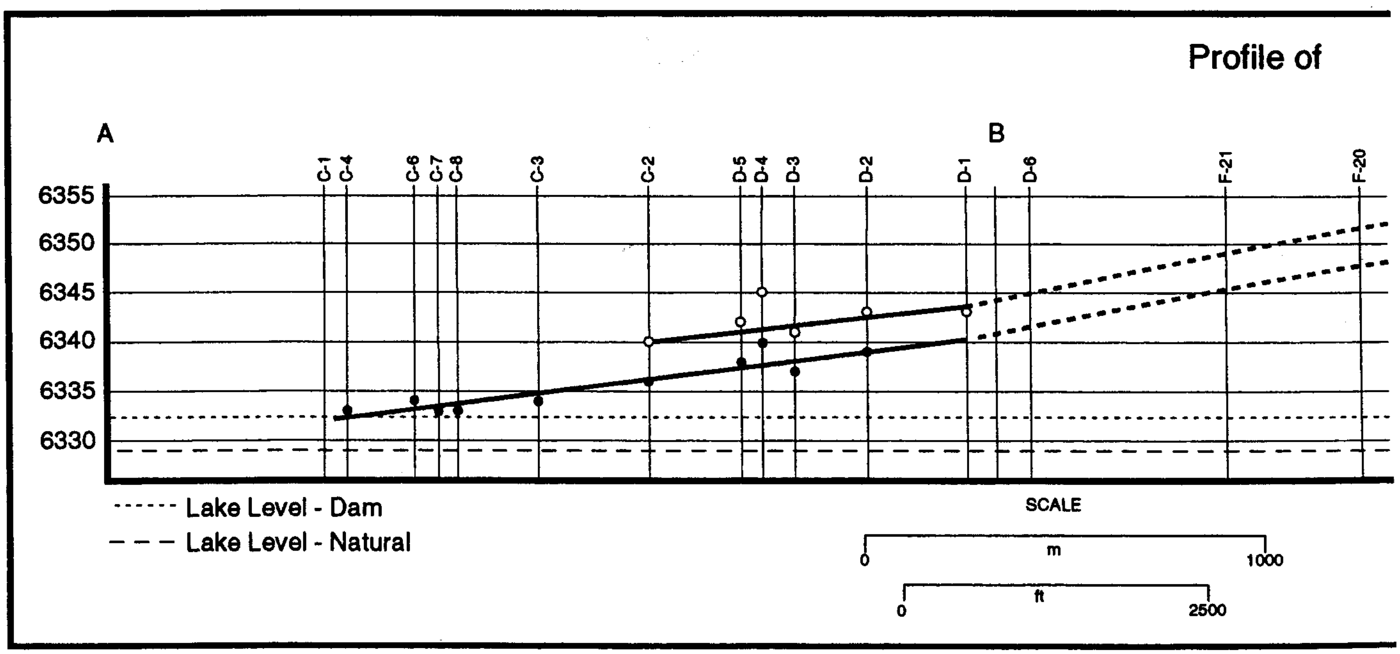


Figure 7. Profile of wave-cut terrace elevations projected onto line ABCD shown in Figure 6. Two sets floor. Maximum measured vertical deformation is 14 ft (4.3 m). The lower set of terraces is well-remnants of an older terrace. Terraces that may have existed along line BC were buried by the

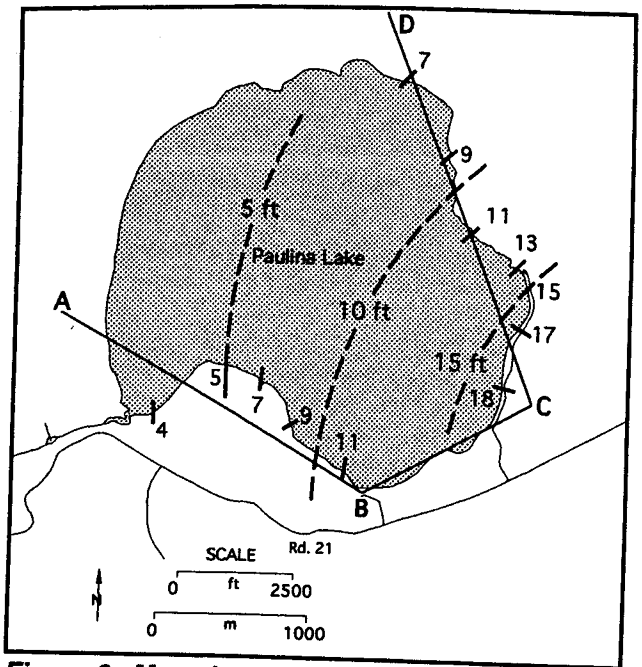


Figure 6. Map showing terrace elevations in feet above natural level of Paulina Lake (6329 ft). Speculative contours are based on terrace elevations. ABCD is profile line used in Figure 7.

Table 3. North shore elevation breaks in cross sections (in ft).

Section Number	Location of Cross Section	Break Elevation
E-5	Trail of ILOF	6349.6
E-6	Campsite at warm springs	6350.1
E-7	Red Slide point	6349.6
E-8	North Cove Campground	6349.8

UPLIFT OF CALDERA FLOOR

Cross sections of wave-cut terraces show a systematic rise in terrace elevations toward the southeast corner of Paulina Lake (Figs. 6 and 7). Along profile line CD in Figure 6, elevations rise from 7 ft (2.1 m) above natural lake level at the northeast corner of the lake to 18 ft (5.5 m) at the south end of Little Crater Campground. Along profile lines AB and BC, elevations rise from 4 ft (1.2 m) at the southwest corner to 18 ft (5.5 m).

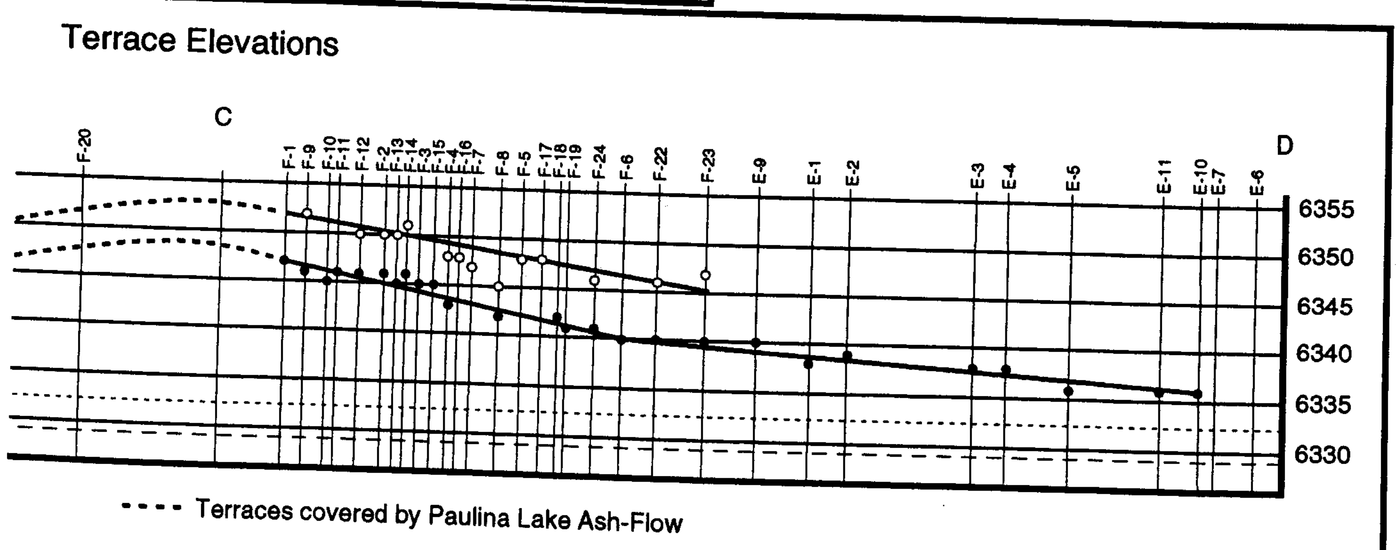
Near the outlet of Paulina Lake, terrace elevations are 4 to 5 ft (1.2 to 1.5 m) above natural lake level (6329 ft). This suggests that lake level dropped at least 4 to 5 ft (1.2 to 1.5 m) during the Paulina Lake flood, which is consistent with a 5 to 8 ft (1.5 to 2.4 m) drop suggested by Chitwood and Jensen (flood article, this guidebook). Subtracting 4 ft from the highest terrace elevation gives a maximum elevation change of 14 ft (4.3 m).

Such vertical change of terrace elevations requires differential uplift of the caldera floor with greatest uplift at the southeast corner of the lake. Undoubtedly, unrecorded uplift to the southeast of the lake has been even greater.

The shape of the uplifted area is poorly constrained, but attempts to create a contour map based on terrace elevations (Fig. 6) are consistent with the shape of a dome centered southeast of the lake.

AGE OF TERRACES AND CALDERA FLOOR UPLIFT

The age of the wave-cut terraces and the caldera floor uplift are constrained by several radiocarbon



of terraces representing different stands of Paulina Lake have been deformed by uplift of the caldera developed and nearly continuous along the east shore. The upper set consists of discontinuous Paulina Lake ash flow.

dates from volcanic deposits, a terrace deposit, and an archaeological excavation.

Mazama ash

All observed terraces have no Mazama ash on them. This suggests that water and waves removed the ash after the eruption of Mount Mazama 7630 calendar years B.P. based on radiocarbon dates (Bacon, 1983; calibrated age based on Stuiver and Reimer, 1993).

Interlake Obsidian Flow

At 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 scattered obsidian gravel bars occur along the northern edge of the 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 considerable time after this in order for waves to cut a terrace and for gravel bars to form.

Terrace deposits

Gravel and sand were deposited when waves were actively developing the terrace. Wood from one of these deposits was radiocarbon dated at 4860 calendar years B.P. MacLeod and others (1995) believed that the terrace was overlain by Mazama ash and that the date was too young. It is now known that the terraces are not overlain by Mazama ash. An archaeological excavation and auger hole at campsite 38 in Little Crater Campground showed 6 ft of reworked tephra from eruptions of the Central Pumice Cone overlying terrace sands. There was no evidence of Mazama ash in the excavation or auger hole. The lake retreated from the terrace sometime after 4860 calendar years B.P.

Rock oven

An archaeological excavation along Paulina Creek at Ogden Group Camp places an important constraint on the time that lake level dropped and on initiation of caldera floor uplift. This and other excavations were begun immediately after the discovery of the Paulina Creek flood (Chitwood and Jensen, this guidebook). The Eastgate Archaeological Site exposed a rock oven and associated charcoal (Bourdeau, 1994, 1995). The oven was buried within Mazama ash colluvium, which had accumulated near the bottom of a slope behind a gravel levee. We interpret the gravel levee to be deposited during the Paulina Creek flood. Charcoal from the oven yielded a radiocarbon date of 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.

If our interpretation of the gravel levee is correct, then the terraces were abandoned by the lake sometime before 1730 calendars years B.P. Uplift of the terraces followed the Paulina Lake flood.

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 Paulina Lake flood and accompanying sudden drop in lake level occurred before this date.

In summary, the terraces were abandoned during the Paulina Lake flood when lake level suddenly dropped. This occurred sometime after terrace gravel and sand were deposited 4860 calendar years B.P.

Terrace abandonment occurred sometime before Native Americans used the rock oven 1730 calendar years B.P. and certainly before the Paulina Lake ash flow 1240 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 abandonment is 2300 calendar years B.P.

Uplift of the caldera floor followed terrace abandonment. Since terrace abandonment took place sometime between 1730 and 4860 calendar years B.P., uplift began sometime after these dates.

EVIDENCE FOR MODERN UPLIFT

Leveling surveys have been done by the David A. Johnston Cascade Volcano Observatory (CVO) of the U. S. Geological Survey (USGS) in 1985, 1986, and 1994 using first-order standards as part of their monitoring program of Cascade volcanoes (Yamashita and others, 1995). The surveys were done along a 23-mile-long (37 km) west-to-east line of bench marks that crosses the edifice of Newberry volcano and passes through Newberry caldera. The westernmost bench mark is located near Prairie Campground (near Ogden Group Camp), and the easternmost is near China Hat.

In 1985, the CVO installed bench marks at approximately a 0.6 mi (1 km) spacing spanning the caldera. These bench marks were surveyed in 1985 and releveled in 1986. In 1994, the CVO resurveyed a portion of a regional third-order leveling network first surveyed by the USGS in 1931 as well as the caldera bench marks installed in 1985.

Within the caldera, elevation differences between the 1986 and 1994 surveys showed that the central area of the caldera had subsided slightly, less than 5 mm (Fig. 8).

Along the 23-mile (37 km) line of bench marks, elevation differences between the 1931 and 1994 surveys showed a general uplift of the edifice of Newberry volcano with a maximum difference of about

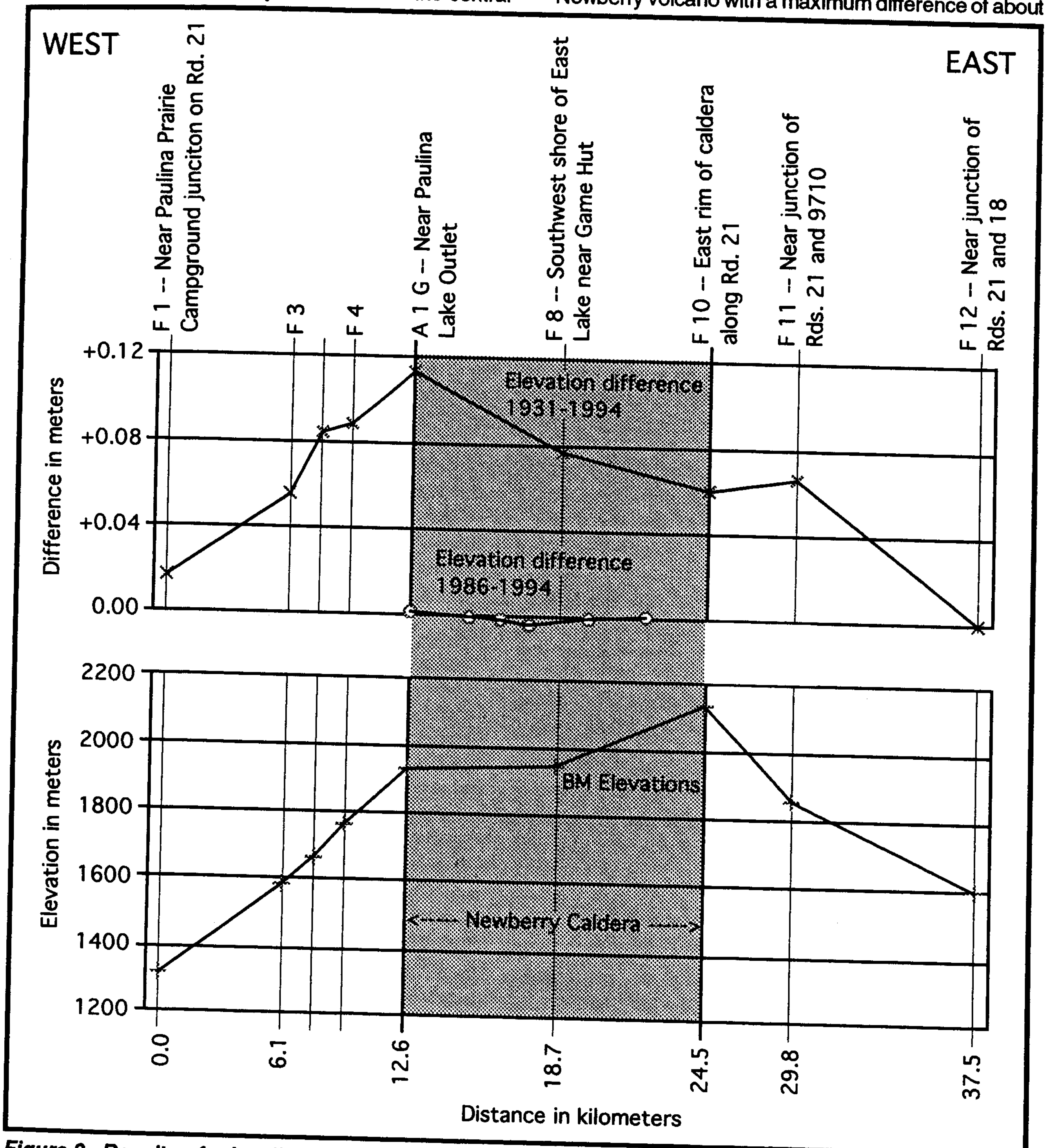


Figure 8. Results of releveling surveys at Newberry volcano. Surveys were done along a west-to-east line of bench marks that passes through the caldera. Upper curves show elevation differences between three surveys. Differences in the 1931-1994 surveys show possible broad uplift across the edifice on Newberry. Differences in the 1986-1994 surveys show minor subsidence in middle of caldera. Lower curve shows elevation of bench marks.

11 cm (Fig. 8). The validity of these differences is questionable because the 1931 survey used third-order standards and the closure was 18 cm. However, the elevation differences of the 1931-1994 surveys and those of the 1986-1994 surveys show consistency within the caldera. Based on these differences, average subsidence was about 0.6 mm/yr for the 8 years between the 1986-1994 surveys and also about 0.6 mm/yr for the 63 years between the 1931-1994 surveys (these differences are those measured at bench marks at and between distances 12.6 and 18.7 km, Fig. 8.).

DISCUSSION AND CONCLUSIONS

If it is assumed that caldera floor uplift began after terrace abandonment and that it has been uniform to the present, the rate of uplift at Little Crater Campground has been >0.9 mm/yr (4860 yr/14 ft). Clearly, this is not being sustained in modern times. In fact, the middle of the caldera floor appears to be subsiding very slowly.

Uplift is generally associated with emplacement of magma under a caldera floor and is one of several important indicators of caldera unrest and an impending eruption (Newhall and Dzurisin, 1988). At Newberry caldera, MacLeod and Sherrod (1988) suggest that a rhyolitic magma body as much as 3 mi (5 km) in diameter has existed under the eastern half of the caldera throughout the Holocene. All rhyolitic eruptions within the caldera during this time have been confined to this area (e.g., the Big Obsidian Flow, East Lake Obsidian Flows, and the Central Pumice Cone).

Uplift of the caldera floor sometime during the past 4900 years and its pattern of deformation may indicate replenishment of the rhyolitic magma chamber centered to the southeast of Paulina Lake. Geophysical studies suggest that the top of the magma body lies 1.2 to 2 mi (2 to 3 km) below the caldera floor (Fitterman, 1988). The uplift described in this report suggests a long-term prelude to future rhyolitic eruptions similar to the ones of the past.

ACKNOWLEDGEMENT

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