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NEWBERRY CALDERA, OREGON: A PRELIMINARY REPORT

By Michael W. Higgins* and Aaron C. Waters**

Introduction

Newberry Volcano is a large shield volcano situated about 40 miles east of the Cascade crest in central Oregon (fig. 1). The volcano is about 40 miles long and 25 miles wide; the direction of its long axis is approximately N. 15° W., but its caldera is elongated at right angles to this trend. The shield occupies and conceals parts of the western extension of a broad belt of en echelon faults, locally called the Brothers Fault Zone (fig. 1). The exact boundaries of the Newberry shield are indefinite because it merges both to the southeast and northwest into other areas of approximately contemporaneous volcanic rocks. These rocks were erupted along the Brothers Fault Zone to the southeast, and from cones and dikes on the east flank of the Cascade Mountains on the west and northwest. In a general way the Newberry shield covers the area approximately bounded on the west by the Deschutes and Little Deschutes Rivers, on the north by hills in and near the city of Bend, on the northeast by Horse Ridge and Pine Mountain, on the southeast by Fort Rock Valley (a western extension of the Christmas Lake Desert), and on the south and southwest by a dissected volcanic complex which culminates still farther south in Bald Mountain, Stams Mountain, and the Walker Rim fault block (fig. 1).

The Crescent, Oregon map sheet (U.S. Army Map Service, NK 10-3, scale 1:250,000, published in 1955) shows the entire area of the volcano. Most of the shield and all of the caldera is covered by the Newberry Crater, Oregon quadrangle (U.S. Geological Survey, 1:125,000, 1931) topographic map. Parts of the volcano are shown in more detail by the following U.S. Geological Survey 7½-minute topographic quadrangle maps: Spring Butte, 1963; Moffit Butte, 1963; Finley Butte, 1963; Paulina Peak, 1963; Lava Cast Forest, 1963; Anns Butte, 1963; Lava Butte, 1963.

Newberry Crater is the name given by I. C. Russell (1905) to the large caldera at the summit of Newberry Volcano. This caldera is essentially an oval depression, with step-like walls, which occupies the top of the shield. The central part of this depression is approximately five miles long by four miles wide, and the caldera walls on all but the low western side rise 1000 to 1600 feet above the floor. Two large lakes and a variety of volcanic features occupy the caldera floor (see fig. 2, numbers 1 to 15 inclusive, 18, and 23).

The purpose of this paper is to give a brief description of the volcano, and to report progress in the detailed mapping and petrologic study of its caldera. The increasing use of the Paulina and East Lake areas for recreation and nature study, and widespread interest in the geology aroused by NASA's use of the Newberry area as a

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* Graduate student, University of California, Santa Barbara.
** Professor of Geology, University of California, Santa Cruz.

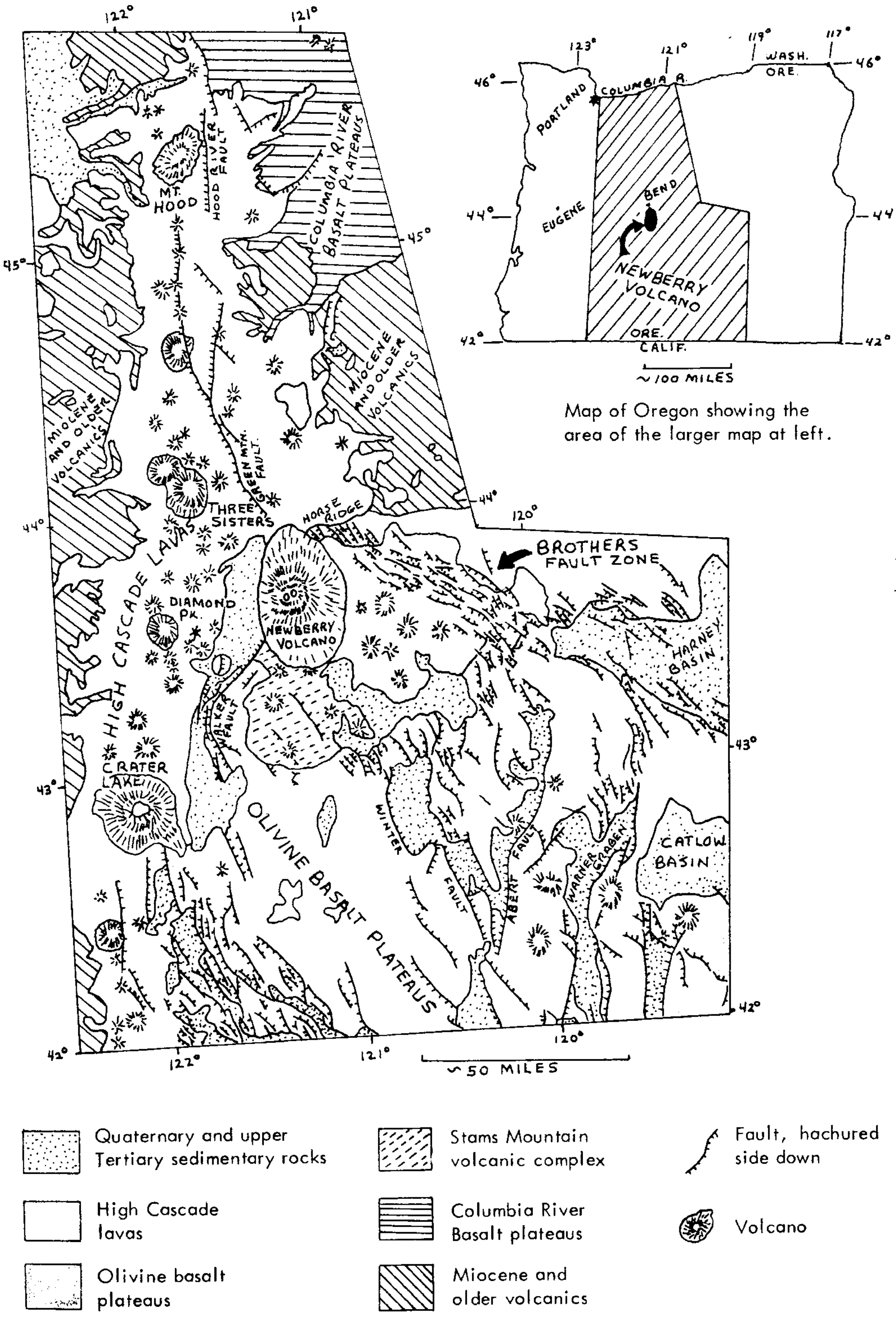


Figure 1. Maps showing the location and geologic setting of Newberry Volcano.

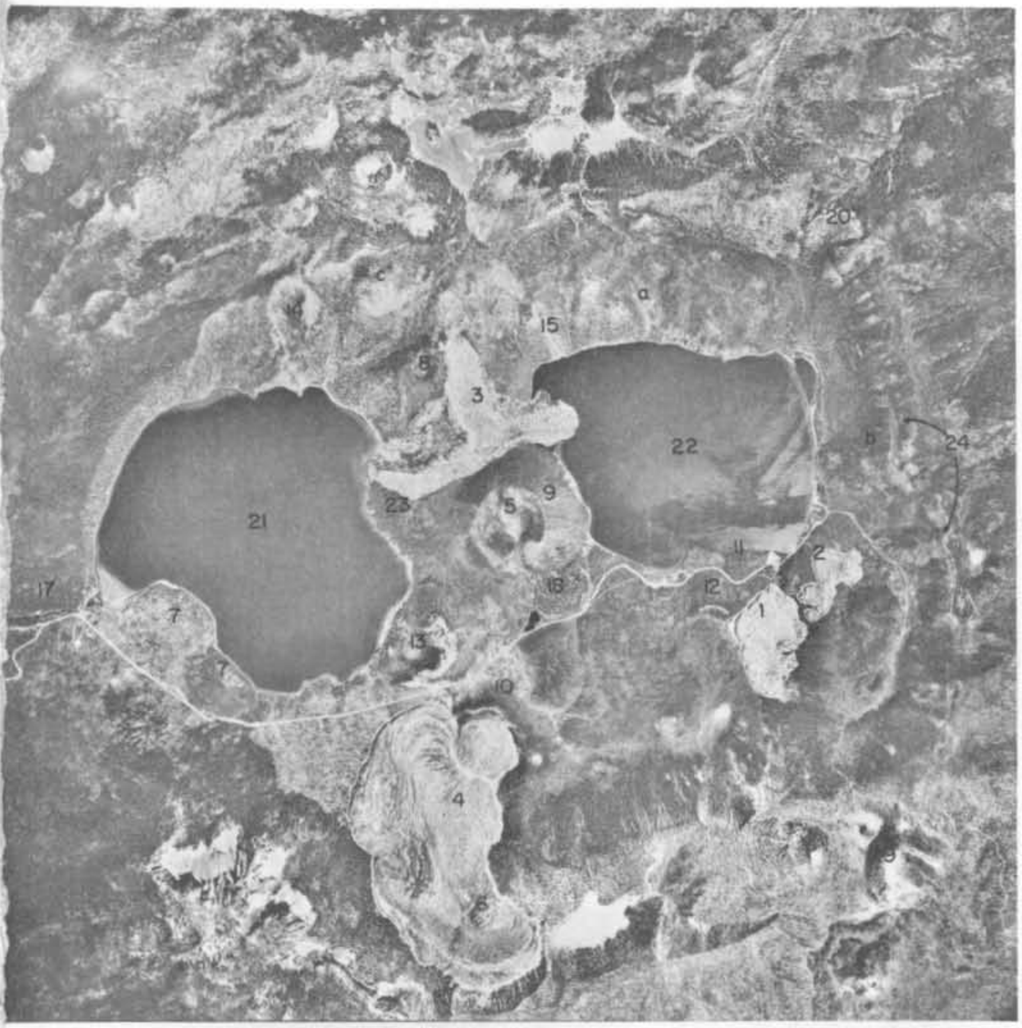


Fig. 2. Aerial view of the Newberry caldera from about 27,000 feet. Numbers on the photograph correspond to features listed below.

1,2 East Lake obsidian flows
3 Interlake obsidian flow
4 Big Obsidian flow
5 Obsidian plug dome in central pumice cone
6 Plug dome of the Big Obsidian flow
7 Paulina Lake obsidian domes
8 North pumice cone
9 Central pumice cone
10 South pumice cone
11 East Lake tuff ring
12 South tuff ring
13 Little Crater tuff ring
14 The Red Slide cinder cones
15 East Lake fissure
16 Paulina Peak rhyolite-obsidian complex
17 Paulina Creek falls
18 Game Hut obsidian flow
19 The Dome (cinder cone)
20 Northeast cinder cones
21 Paulina Lake
22 East Lake
23 Interlake basalt flow
24 Chain craters on fissures, top of east rim.

Letters refer to outcops of the mafic graded tuffs; see figures 4, 5, and 6.

training ground for the astronauts and by the field trip in connection with the State of Oregon Lunar Geological Field Conference, merits a preliminary report before completion and publication of the detailed petrologic studies in which the authors are engaged.

Previous geologic study

I. C. Russell first described Newberry Crater in 1905. He thought the depression containing Paulina and East Lakes lay between two adjacent volcanoes. The most complete study of the volcano to date was made by Howel Williams (1935). A.C. Waters and G. W. Walker contributed, mainly from unpublished field studies, the geologic information shown for Newberry Volcano and its surroundings on the Geologic Map of Oregon West of the 121st Meridian (1961), and on the Tectonic Map of the United States (1962).

The Foundations of Newberry Volcano

As Williams stated (1935, p. 258): "There is only meagre evidence concerning the foundations upon which the Newberry shield is built." He went on to note that the oldest rocks found in the immediate vicinity of the volcano are "coarse pyroxene andesites and andesitic basalts of Indian Springs and Amota buttes, and the basalts and rhyolites or dacites of the Pine Mountain fault block." Williams suggested (p. 258) that these rocks might be found immediately beneath the shield. He also suggested that Miocene Columbia lavas may lie beneath the volcano, because these rocks are found dipping to the east on the western side of the Cascades.

Recently, Hampton (1964) published the results of geologic mapping and well-core data from the Fort Rock basin immediately southeast of the volcano (the maps actually cover a part of the south edge of the shield). He presented a stratigraphic column (p. B5) of the rocks of the Fort Rock basin. These units extend beneath Newberry, and form at least the upper part of the basement beneath the southern edge of the shield. Unpublished work by G. W. Walker and by A. C. Waters shows that Eocene to Pliocene rocks underlie large areas northeast of Newberry Volcano, across the Brothers Fault Zone. These probably extend south and west beneath the volcano and beneath the rocks of Fort Rock valley. Among them are the Clarno Formation (Eocene), the John Day Formation (Oligocene-Miocene), the Columbia River Group (Miocene), and a variety of Pliocene-Pleistocene volcanic and volcaniclastic rocks of which high alumina basalts, such as those which disappear beneath the Newberry shield at Horse Ridge, are the most widespread. Rhyolitic and rhyodacitic tuffs, welded tuffs, tuffaceous sediments, and lesser amounts of lava are locally prominent.

Thus a wide variety of Tertiary and Quaternary rocks probably are represented in the basement beneath the Newberry shield, but these basement rocks do not occur in a simple undeformed stratigraphic succession. Their structure is undoubtedly greatly complicated by the faulting, volcanism, and intrusion that accompanied the development of the Brothers Fault Zone, as well as by the fissuring and faulting that occurred during the growth of Newberry Volcano and its caldera.

The Brothers Fault Zone

The Brothers Fault Zone (fig. 1), 2 to 20 miles wide, is a group of interlacing en echelon faults. It extends across central Oregon on a general N. 75° W. course from the Harney Basin to Newberry Volcano, a distance of more than 100 miles. Along its southern margin, the large north-south faults that define Steens Mountain, Abert Rim, and other young fault blocks of the Basin and Range Province in southern Oregon split up into strands which then bend abruptly westward and merge into the Brothers Fault Zone. Quaternary lavas have risen to the surface along the Brothers Fault Zone, forming complexly interfingering alignments of low lava shields and flows. Many faults are surmounted by rows of cinder cones, some of which have been broken by renewed faulting. Southeast of Newberry Volcano, however, most of the faults in the Brothers Fault Zone are hidden by these young volcanic outflows, and by the rocks of the Newberry shield. Nevertheless, the faults can be seen in great numbers where they bypass the northeast margin of the Newberry shield through Horse Ridge, Pine Mountain, and the southern end of the Bear Creek Buttes. Equal or greater numbers of early faults must lie hidden beneath Newberry in the basement rocks. Some continued to be active during growth of the shield as shown by the presence of dikes, fissures, and rows of cinder cones on the surface of the Newberry shield which have the same alignment as the faults of the Brothers Zone.

The continuation of the Brothers Fault Zone west of the Newberry shield is not well known because it is mostly hidden beneath young volcanic rocks from the High Cascades. Apparently, however, it turns abruptly to the northwest beneath Newberry. This change of direction is best seen in the faults so well exposed on Horse Ridge and in the southern part of the Bear Creek Buttes just northeast of the Newberry shield, but it is also apparent in the fissures and the rows of cinder cones perched on the shield.

Some strands of the fault zone emerge from beneath the late lava cover west of the Deschutes River, and here they bend northward to join the belt of north-south trending normal faults east of the Cascade Crest that define the Bald Peter and Green Mountain fault blocks along the headwaters of the Metolius River, and the fault scarps which form the east wall of the Hood River valley farther north.

Newberry Volcano, therefore, appears to be located where the Brothers Fault Zone bends sharply to the north. It is interesting that the volcano is also directly in line with the large fault that defines Walker Rim (fig. 1). The Walker fault trends about N. 40° E., nearly at right angles to the faults of the Brothers Zone where they bend to the north. Lineaments with this trend can also be seen on the Newberry shield, especially on its southern and northeastern parts. Evidence will be given later that they are present within the caldera as well.

Sequence of Rocks in the Caldera Walls

The Newberry shield is so recent in age that streams on its flanks have cut only insignificant canyons. Moreover, earlier canyons have been inundated and filled by recent lava flows. Even Paulina Creek, which drains the caldera, exposes few rock units along its course except at Paulina Falls where a thickness of about 100 feet of rocks is exposed beneath the lip of the waterfall, and at the lower falls on the creek where about 70 feet of rocks are exposed. Therefore, the only exposures that reveal a continuous section of rocks more than 100 feet thick are found on the walls of the caldera.

The detailed structure of these caldera sections is not everywhere clear because of complexities due to faulting and extrusion accompanying subsidence of the caldera, and also because the rocks are masked in many places by talus and younger air-fall pyroclastics. Nevertheless, an unusually regular sequence of stratigraphic units can be recognized, and they record an orderly succession of events in the building of the upper part of the volcano. This sequence belies the impression gained from traveling over the flanks of the volcano that it is a simple shield made up almost entirely of basalt.

Rhyolite

The oldest rocks exposed in the caldera walls are rhyolite flows. They occur as continuous exposures (except where covered by minor landslides) along the base of the north wall, and as discontinuous exposures at the base of the south wall (see geologic map, fig. 3, p. 48-49). At all localities observed, the rhyolites dip into the walls at 20° to 25°. The maximum observed thickness of rhyolite is about 375 feet, but the base is never seen. Rhyolites are not found on the east wall, where younger rocks occur at the level of the caldera floor.

Most rhyolites are gray and platy, with pinkish-white and white spherulites arranged parallel to the platy structure. Tiny laths of plagioclase are also oriented parallel to the platy structure, and are one of the most important elements in defining it. Although this is the characteristic kind of rock, variations are more the rule than the exception; colors range from black to pink, structures from massive to platy, and textures from glassy to microporphyritic. In many places variations occur within a 10- to 12-foot distance along the strike; vertical variations in color, platiness, crystallinity, and vesicularity are also common. Bands of lustrous black obsidian occur at certain horizons; they generally have breccia zones at their base, and may pass upward into breccia or into contorted platy rhyolite. In general, the rhyolites have the appearance of sticky lavas which were erupted from nearby sources and piled up immediately around the vents. Indeed, it is possible that they may be remnants of flows erupted from ring fissures formed during an early stage in the growth of the shield.

Although, following Williams (1935), these rocks have been loosely designated as rhyolite, the abundance of plagioclase and absence of silica minerals in some thin sections indicates that the more detailed petrographic and chemical work now in progress may show that this stratigraphic unit contains rhyodacite and dacite, and even some rocks that are transitional to the platy andesites next described.

Platy andesite

Directly above the rhyolites on the north and south walls of the caldera are black to gunmetal-gray lava flows with marked platy jointing and contorted flow banding. These are aphanitic and mostly nonporphyritic augite andesites and olivine-augite andesites. Platy andesites also form the base of the east wall, and they are present at the lower falls on Paulina Creek west of the caldera. The stratigraphic unit of andesite varies in thickness from about 375 feet to less than 30 feet. No evidence for any extensive time interval between the andesite and the rhyolite below it was seen. The andesite thins to the west and is thickest on the east wall, suggesting that the east side of the volcano may have been lower than the west side when it was erupted.

Fig. 4. Outcrop of the mafic graded tuffs on the north wall of the caldera, approximately above the center of East Lake (marked as A on figure 2). Note the numerous thin beds and the dip into the wall.

In outcrop the andesites vary from exceedingly fine-grained splintery rocks to platy-jointed flows that weather into thin chips. The upper parts of some flows show highly contorted flow banding and zones of rewelded autobreccia. Small chips of rhyolite, derived from the unit below, were found in some andesite flows.

In thin section most andesite flows have a pilotaxitic texture marked by a strong alignment of andesine microlites, and also by a well-developed platy structure. The platy joints follow collapsed vesicles and have also developed where thin zones of markedly oriented microlites of somewhat larger size than those of the pilotaxitic groundmass have grown along shears that opened and rewelded during a late stage in flow of the lava. The platy joints may lie parallel with the flow banding, or may cross it at any angle. An unusual feature of these andesites is their nearly holocrystalline texture, but unusually fine grain size. Andesine laths are generally less than 0.07 millimeters long, and most pyroxene grains are only 0.01 to 0.03 millimeters in diameter. Tiny euhedral opaques are scattered through the rocks in unusually large amount--they constitute up to 4 percent by volume of many rocks. Olivine is a minor constituent of more than half of the andesites sectioned, but it rarely exceeds 1 percent by volume. It generally occurs in resorbed and partly to completely iddingsitized grains. In general, the andesites are nonporphyritic, but glomeroporphyritic clots and small cognate xenoliths are not rare. Most of these are composed of labradorite and monoclinic pyroxene, with or without a little olivine. They are identical to the phenocrysts and clots that occur in many of the high-alumina olivine basalts of the Newberry shield.

Scoria

At all contacts observed the dense platy andesite is followed by 30 to 50 feet of red and red-brown scoria. Bombs and cinders in this scoria were pasty enough to stick together, and at many localities the scoria welded into a fairly coherent agglutinate. Evidently the violently fountaining vents through which the bombs and lapilli were expelled were not far from the outcrops observed.

Mafic tuffs with graded bedding

Immediately above the red scoria on the north, south, and east walls, and also in the gorge of Paulina Creek outside the caldera, is a widespread series of graded beds composed of buff to brown mafic tuff. Over 150 individual graded beds of tuff and tuff-breccia can be counted in some outcrops (figs. 4 and 5). The base of each bed is composed of fragments of andesite or basalt as large as blocks or lapilli; this is usually followed by lapilli- to ash-sized particles. Then there is a fairly sharp break followed by fine to very fine granular ash. In addition, the entire accumulation of tuffs is graded -- coarse portions of the lower beds are much coarser than in analogous beds near the top. Large blocks have fallen into some of the finer beds, producing prominent bomb sags (fig. 6). The thickness of the entire unit is estimated at about 175 feet maximum, although there is no single outcrop where both the base and the top can be observed. The unit appears thinnest on the southwest, but whether this is due to original topography at time of deposition or to other causes is not known. The beds dip into the caldera walls at all points observed.

Neither field nor petrographic studies have yet progressed to the point where the origin of these graded tuffs can be stated with assurance. Their uniform distribution in all three walls of the caldera, their even bedding, and the draping of the beds over minor irregularities, suggests an air-fall origin. Most fragments of the tuff, however, are bits of sideromelane-like glass in various stages of alteration to palagonite, clay minerals, and zeolites. This evidence of chilling and alteration indicates that the magma which fed the tuffs came into contact with surface water or else with copious supplies of ground water which quenched and granulated it to a sideromelane breccia. Indeed, the general field appearance of these mafic tuffs is very similar to exposures of bedded palagonites making up the tuff ring of Fort Rock, which grew upward from the floor of a late Pleistocene lake. Moreover, the kind of graded bedding, and particularly the superimposed upward grading of the entire assemblage of graded tuffs, is strongly reminiscent of pyroclastics erupted under water, and then distributed outward by gravity flow (Fiske, 1964; Fiske and Matsuda, 1964).

On the other hand the abundance of coarse blocks and bombs in some of the finer beds and the marked sagging without disruption of the beds beneath them (fig. 6), suggests that these projectiles were airborne, but that they fell not into a fluffy accumulation of dry pyroclastics, but instead into sticky water-soaked beds capable of sagging and dewatering beneath impact and load, but coherent enough to retain their bedding almost undisrupted.

These problems of origin cannot be resolved until further field and laboratory studies (to be undertaken in the summer of 1967) are completed. As a tentative speculation, it is suggested that the mafic graded tuffs record the appearance of an early but shallow caldera lake. This allowed entry of surface waters into the andesitic and basaltic vents which had been erupting the underlying red-brown scoria and agglutinate as an air-fall deposit. Underwater eruptions from the same vents now projected chilled and granulated bits of volcanic glass and fragments of the underlying rock; the more violent steam explosions probably drove eruption clouds into the air far above the water surface. Debris falling back into the water gradually built up a tuff ring

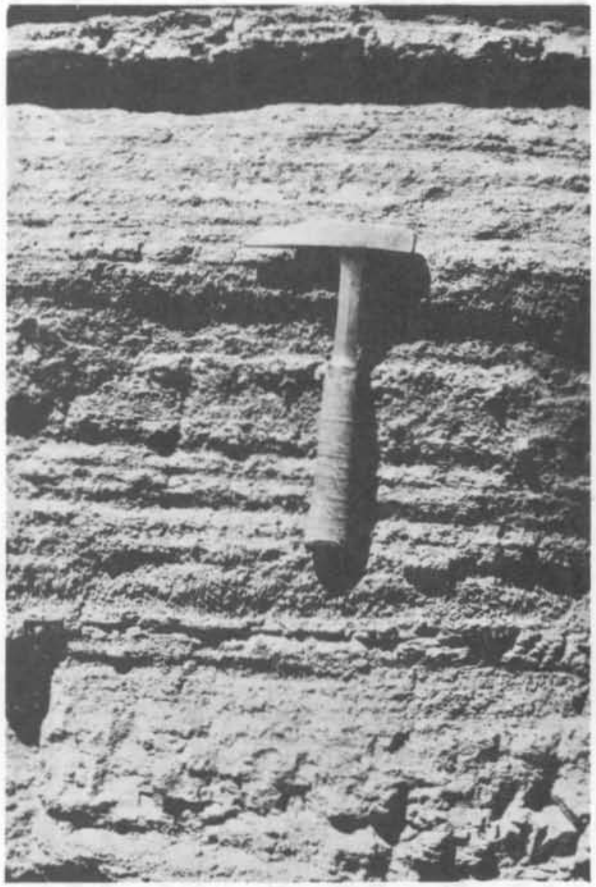


Fig. 5. Details of beds of mafic graded tuff in an outcrop on the north wall of the caldera (marked C on figure 2).

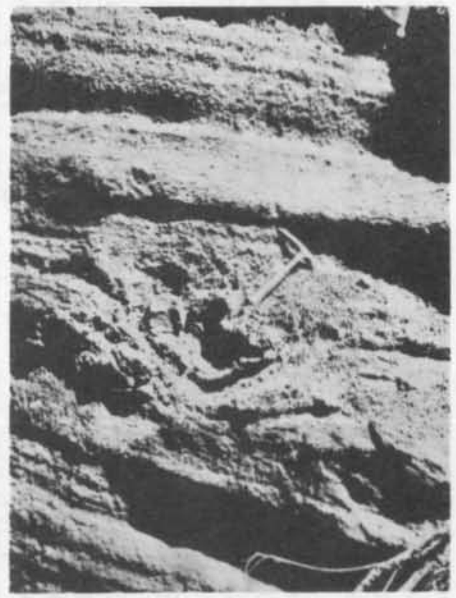


Fig. 6. Beds of the mafic graded tuff on the east wall, showing depression of beds by a bomb that hit before they were consolidated.

which filled the shallow lake and continued to grow above the water surface just as the cones of Surtsey, off the shore of Iceland, and Anak Krakatau, on the submerged edge of the Krakatau caldera, are building up today (Decker, 1961). Much of the debris, blown high in the air by the more violent explosions, was deposited on land as a wet, sticky air-fall tuff.

Welded tuff

Welded tuff overlies the mafic graded tuffs on the east wall, and on part of the north wall of the caldera. On the east wall it is 60 to 70 feet thick, and thins both to the north and to the south. Large pumice fragments in the tuff have been completely collapsed; in outcrop they resemble streaks and bands of lustrous black obsidian enclosed in a gray, aphanitic matrix, but in thin section collapsed bubble walls and compaction features around phenocrysts are clearly visible, and the rock shows slight reddish oxidation and other evidence of devitrification. The gray matrix is a heterogeneous assemblage of flattened shards, shreds of pumice, broken crystals, and abundant fragments of andesite, basalt, and other rocks, all showing effects of oxidation, welding, and devitrification. Both the collapsed pumice and the matrix materials are intensely compacted and welded around the basalt and andesite inclusions. Eutaxitic texture indicating final forward creep of the welded but still plastic mass (Swanson and Schmincke, 1967) is apparent in parts of the welded tuff.

Red andesite and olivine-poor basalt

On the low west wall of the caldera, and in the gorge of Paulina Creek, the mafic graded tuff is overlain by andesite (Williams, 1935, p. 263) and by olivine-poor basalt ranging in color from gray to brick red. The typical rock is a reddish flow with large phenocrysts of plagioclase, but in the gorge of Paulina Creek the variety most prevalent is a red andesite breccia. These oxidized rocks have been only cursorily examined under the petrographic microscope. They are coarser grained, contain more phenocrysts of plagioclase and olivine, and are much more oxidized and altered than the platy andesites of the caldera walls and the lower falls of Paulina Creek.

Brown scoria

In the south wall of the caldera, near Paulina Peak, the mafic graded tuffs are followed by about 60 feet of brown basaltic scoria. Many large bombs in the scoria indicate that the vent from which they came was not far away.

Rhyolite of Paulina Peak

Rhyolite underlies Paulina Peak and spreads downslope to the southwest for a distance of at least three miles. It is mostly platy rhyolite, but contains interlayers of obsidian and of frothy to pumiceous material. In the larger outcrops it is quite variable, ranging from black to pink or white in color, from massive to platy in structure, from porphyritic to spherulitic and felsitic in texture, and from hemicrystalline to glassy and pumiceous in crystallinity. Some welded tuff may be present near the base of this stratigraphic unit.

The rhyolite rests unconformably upon the brown basalt scoria on the south wall of the caldera. Here, in its easternmost exposure, it is only about 60 feet thick. It thickens rapidly to the west, and at Paulina Peak over 1300 feet is exposed in the caldera wall. From various features (streaky flow banding and platiness, overturned folds in the flow banding, lineations, pulled out tensional cracks across flow bands, drag structures due to differential flow band movement, and large ramp structures) the rhyolite and associated obsidian appears to have spread outward in somewhat lobate tongues from a point somewhere north of the present caldera rim where it slices across Paulina Peak. Yet, similar rhyolite at this stratigraphic position is missing across Paulina Lake on the north wall of the caldera, indicating that the rhyolite probably did not emerge from the old summit area of the volcano. The rhyolite may have risen along ring fractures associated with an early stage of caldera collapse, and was then cut by later movement of the same faults. On a later page evidence is given that it probably poured out at or near the junction of such ring fractures with a major north-south fault which downdropped the western part of the top of the shield.

Other units

Several other thin local units are present in the caldera walls, but will not be described in this preliminary report of the generalized wall sequence.

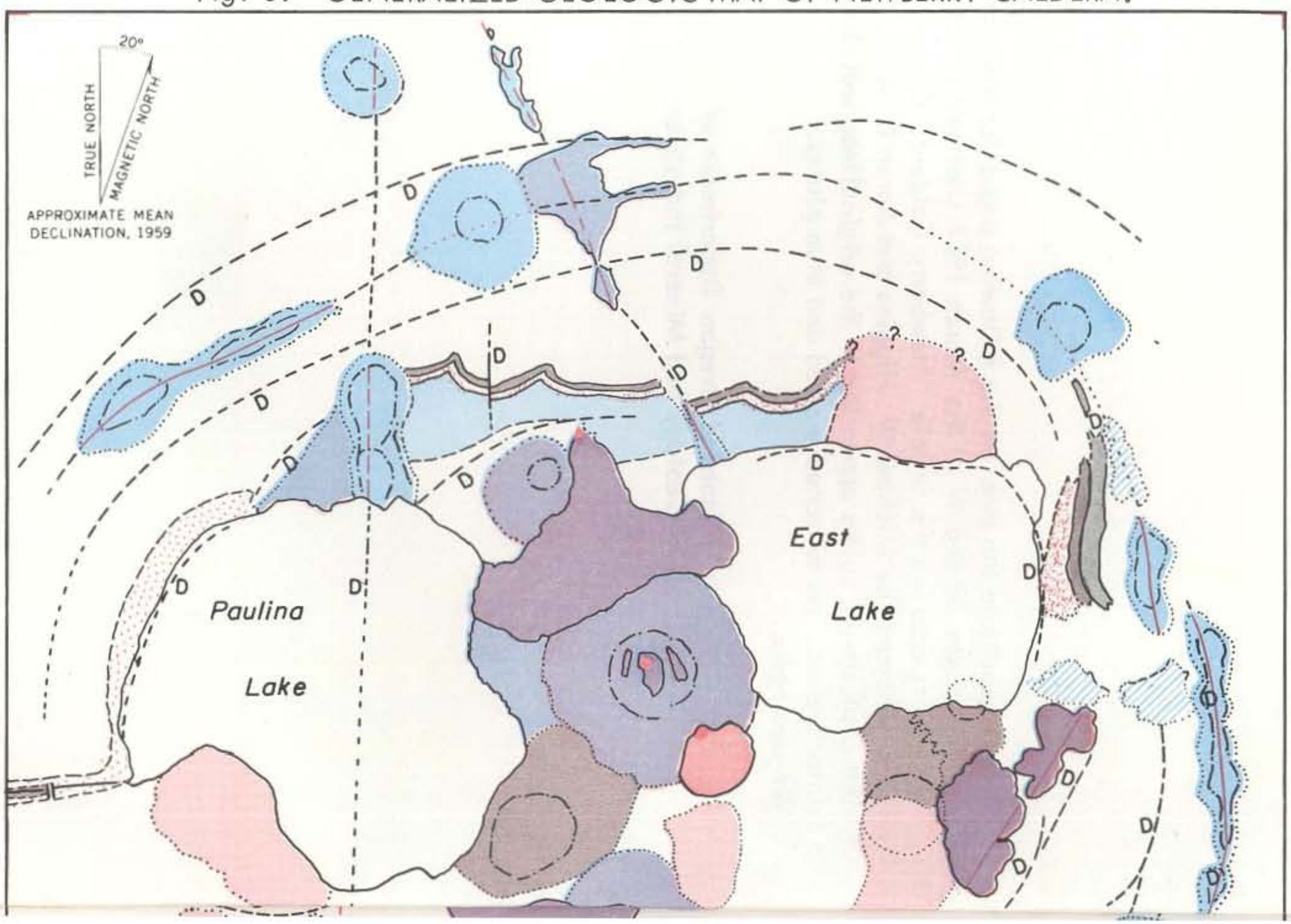
The Formation of the Caldera

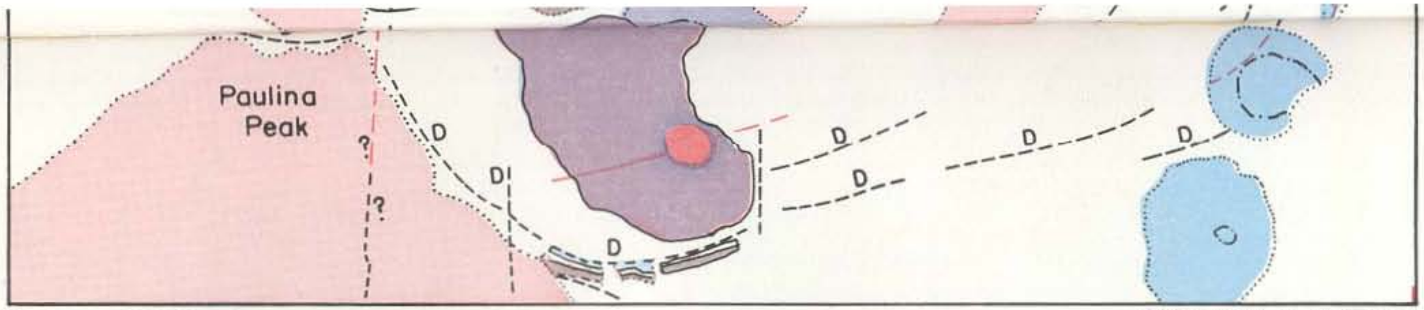
As already mentioned, one of the caldera walls at Newberry Crater cuts (or beheads) the Paulina Peak rhyolite flows -- therefore, final subsidence of the caldera occurred after this rhyolite (and those units under it) were emplaced. In places the caldera contains about 15 to 20 inches of Mazama ash easily identifiable by its high percentage of well-formed crystals of pyroxenes and plagioclase (Powers and Wilcox, 1964; Fryxell, 1965). This Mazama ash, erupted just before the formation of the Crater Lake caldera, has been dated at 6,600 years ago. Whether the Mazama ash fell after collapse of the Newberry caldera or fell earlier and was spilled into the caldera along with the old summit, is not yet known.

Subsidence of Newberry caldera probably began with downdropping of a large, roughly circular block -- much larger than the present caldera -- along ring fractures. The outline of this early caldera can be seen as a "step" about a mile and a half from the present inner caldera walls. Successive "circular" downdrops with increasingly greater displacements, but with smaller diameters, resulted in the present "nested" or stepped arrangement of the caldera walls (figs. 7, 9, and 10). We cannot, however, be sure as yet when movement on these outer faults actually started, because even after formation of the present inner caldera the old faults defining the earlier and larger, but probably much shallower calderas, continued to be active. From these fractures issued late andesite and basalt flows, and the fountaining of scoriaceous lava from the fissures built up levee-like spatter banks and small cones of cinders and bombs along the fissures (fig. 7), only to be cut and displaced in turn by still more recent movements. The pyroclastics and flows now visible along these fractures are not covered by Mazama ash, and must, therefore, be less than 6,600 years old.

The cause of caldera formation at Newberry is open to speculation. Did the caldera form, as Williams (1935, p. 267) suggested, after large volumes of basaltic lavas had been erupted from vents far down the slopes of the shield, thus draining the upper levels of the magma conduits and withdrawing support for the roof of the shield?

Fig. 3. GENERALIZED GEOLOGIC MAP OF NEWBERRY CALDERA.





Base from aerial photograph.

Geology by M. W. Higgins and A. C. Waters, 1967.

1 mile

Explanation

- Landslide deposits, areas covered by pumice, and areas not yet mapped
- Obsidian flows
- Basalt and/or andesite cinders with some thin flows and agglutinates
- Late andesite flows on the floor and rims of the caldera
- Pumice cones
- Basalt flows
- Rhyolite flows and domes with some obsidian
- Mafic tuff rings
- Welded tuff
- Andesite and/or olivine-poor basalt
- Mafic graded tuffs
- Platy andesites of the caldera walls
- Old rhyolites of the caldera walls
- Crater
- Obsidian dome and/or vent
- Fault with down-dropped block marked "D". Dashed where inferred.
- Fissure which acted as a vent. Dashed where inferred.
- Contact, dashed where approximate. Dotted where gradational or inferred.

This appears likely, but the eruption of the welded tuff on the east wall of the present caldera, and the eruption of copious flows of rhyolite forming Paulina Peak may also have been contributing factors, and so may movements of the basement rocks along the complex assemblage of en echelon faults that comprise the Brothers Fault Zone where it passes beneath the volcano.

Post-Caldera Activity

East Lake and Little Crater tuff rings

After foundering of the caldera to its present depth was essentially completed, post-caldera volcanic activity brought about many changes on the caldera floor. Among the earliest events was the growth of three mafic tuff rings formed mainly under water. Whether all three erupted concurrently or separately is not known at this time. Therefore, the order of description has no chronological or stratigraphic significance.

East Lake tuff rings

Two mafic tuff rings are present on the south shore of the present East Lake. For purposes of description, the ring nearest the lake is called the East Lake tuff ring, and the ring just southwest of the East Lake ring is called the South tuff ring (fig. 2 and fig. 3). Neither ring is complete.

About half of the East Lake tuff ring is present now, but the draping of the beds over the old rims indicates that the center was beneath East Lake approximately 100 yards off the south shore. Coincident with this deduced center are active hot-springs and fumaroles in the lake.

The South tuff ring is also represented by about half of the original cone. The southern half was overwhelmed by a later obsidian flow erupted from a vent about a third of a mile to the south.

The beds and rocks of both rings are very similar. Both are composed of hundreds of thin (from less than half an inch to about six inches thick) beds of palagonitic lithic tuff. Many beds are graded, and the size of the lithic fragments ranges from about an inch and a half in diameter to lapilli and fine ash. Many larger fragments up to $4\frac{1}{2}$ feet across are sporadically distributed through the beds. The matrix is a fine basaltic ash. Fragments of rhyolites and of hypabyssal rocks are not rare.

The glassiness of most fragments, the formation of palagonite and clays, and the nature of the "draping" of the beds over the old rims, suggest that the tuff rings were formed by rhythmic phreatic eruptions from vents in a shallow lake.

Little Crater tuff ring

Little Crater tuff ring lies at the southeast shore of Paulina Lake on the neck of land separating the two lakes (figs. 10 and 11). It is complete, and shows a draping of beds over its rims, similar to the East Lake rings and to other aqueous tuff rings (for example, Fort Rock). Like the East Lake rings it has many "foreign" inclusions, but not of such variety as the East Lake rings. It also probably formed from rhythmic eruptions in shallow water.

Wall deposits from the tuff rings

On the north wall, thin beds of palagonite tuff, identical to those forming the tuff rings, are locally present. They are bedded parallel to the steep walls, and must have been wet and pasty to have had the consistency to maintain their bedded position on slopes as high as 50°. In other words, they must have been "plastered" there, as air-fall deposits of wet sticky material.

Relative age of the tuff rings

The South tuff ring has been overrun in part by one of the East Lake obsidian flows (fig. 3). Since beds from the two East Lake rings are intercalated with one another, they are assumed to be roughly the same age. Thus, both rings are probably older than the East Lake obsidian flows. All three rings are mantled by pumice from one or more of the pumice cones and thus are older than these pumice cones.

East Lake obsidian flows

Two obsidian flows are present on the southeast side of East Lake (fig. 7 and 8). The flows are tentatively considered to be of the same age and to have been erupted from the same fissure (fig. 8). Because the westernmost flow overran part of the apron of the South tuff ring, the flows are considered younger than the tuff rings. Both flows are mantled by as much as two feet of pumice erupted from pumice cones within the caldera.

Interlake basalt flow

The interlake basalt flow (fig. 2) was erupted from a vent or fissure at approximately the center of the neck of land dividing the two lakes (now covered by the central pumice cone). The flow emerges from beneath the pumice apron of the central pumice cone, and covers the western part of the neck of land between the lakes. Numerous lobes extending to the eastern shore of Paulina Lake indicate that the direction of flow was towards the lake. Oxidation, alteration, and brecciation of the basalt at the shore of the lake, the probable projection of many of the lobes into the lake, and the fact that the flow locally overlies semi-consolidated lake deposits, indicates that the flow entered the lake. To the north the flow is overlain by the interlake obsidian flow.

In hand specimen the rock is a scoriacious or vesicular olivine basalt. Thin sections have not yet been studied.

Pumice cones

There are three main pumice cones on the floor of the caldera (figs. 9, 10, and 11). One, informally called the north pumice cone, lies at the northeast corner of Paulina Lake at the foot of the north wall (fig. 9). The largest (central pumice cone) lies in the middle of the neck of land between the two lakes. The third (south pumice cone) is now represented by half of the original cone, and lies just south of the Interlake road.

The north cone is nearly perfect and has a crater more than 100 feet deep (fig. 9). It is composed entirely (at least as far as can be seen) of pumice ranging from

Fig. 7

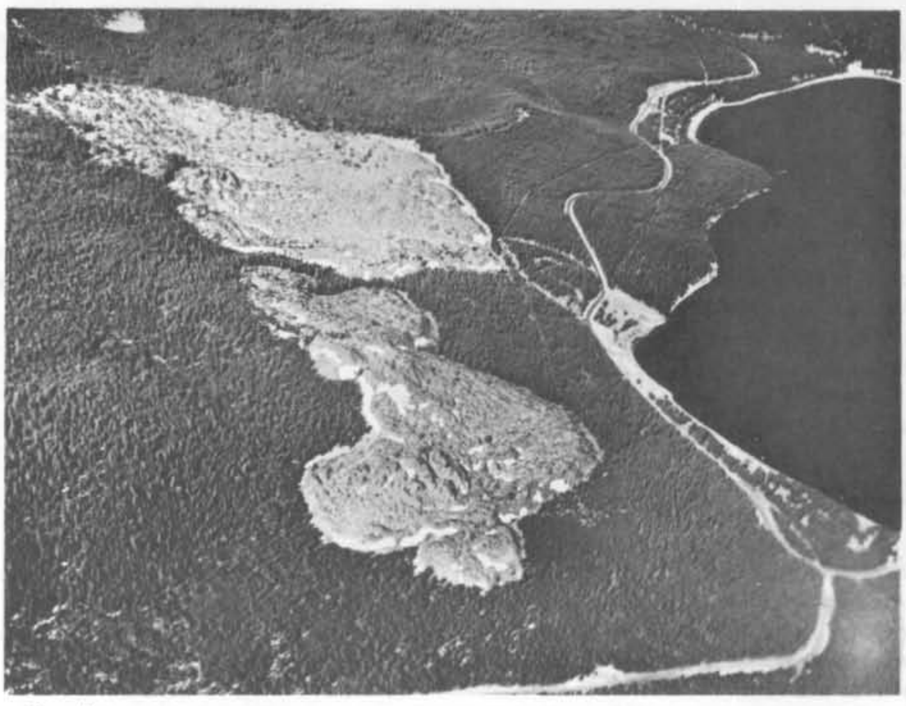


Fig. 8

Fig. 7. The stepped south wall of the Newberry caldera culminates in the rhyolite pile of Paulina Peak (right skyline). Two late obsidian flows, erupted from a single NE-SW trending fissure are in the center of the picture, just left of the southeast corner of East Lake. Big Obsidian flow spills over the lower step of the caldera rim in front of Paulina Peak. The top of the east caldera rim, angling across the left foreground of the photograph, is marked by an open fissure along which lie numerous chain craters, some of whose rims are dimly outlined by the cover of new-fallen snow. (Oregon Dept. of Geology and Mineral Industries photograph)

Fig. 8. The East Lake obsidian flows. Both were erupted, probably contemporaneously, from a NE-SW trending fissure whose trace can be seen as a line of discontinuous cracks across the highest parts of the flows. (Oregon Dept. of Geology and Mineral Industries photograph)

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blocks to fine lapilli along with some fragments of older rhyolites.

The central pumice cone rises more than 700 feet above the lake. It is symmetrical, but with a deep cleft running across the crater in a north-south direction (figs. 9 and 11). This crater, more than 200 feet deep, contains a small obsidian dome which barely emerged through the crater floor. Another small obsidian dome poked up through the southeast margin of the cone and spread for a quarter of a mile to the east, southeast, and south. The central cone is composed mostly of pumice, but several "interbedded" obsidian layers can be seen in the walls of the crater.

The south pumice cone is partly obliterated by a lobe of the Big Obsidian flow which inundated its western half and spilled into its crater (fig. 10). The remaining half of the cone is composed entirely of pumice and fragments of rhyolite.

The pumice sheets that spread out as airfall deposits from the three cones have not yet been divided in the field (if, indeed, they are divisible). Airborne pumice from these cones extends as a continuous blanket for at least 20 miles to the east. At the thickest point on the southeast wall this pumice blanket is 18 to 20 feet thick.

In addition to the airfall pumice deposits, there are at least two pumice-lapilli ash flows in the caldera. These pumiceous ash flows are divided by and overlain by interbedded airfall pumice. Both pumice flows contain charcoalized logs. A log from one of the flows has been dated at 2054 ± 230 years ago (Peterson and Groh, 1965, p. 11).

<u>Interlake obsidian flow</u>

The interlake obsidian flow issued from a point near the base of the north wall and flowed down the neck of land between the two lakes until it encountered the base of the central pumice cone which divided it into two branches (fig. 9). One branch flowed towards East Lake and filled the narrow valley that existed between the central pumice cone and the north wall. The other branch was channeled into the narrow valley between the central pumice cone and the north pumice cone (figs. 9 and 11). In this course it encountered and overrode the ridge-like lobes of the interlake basalt flow. Whether either branch entered water or not is not known. There is some indication that the lakes either had drained, or stood at a much lower level during this time.

Because it was deflected by the central and north pumice cones, has no pumice cover, and overrode the interlake basalt flow, the interlake obsidian flow is clearly younger than the pumice cones.

Fig. 9

Fig. 10

Fig. 9. The cleft top of the central pumice cone is in the center of the view. The interlake obsidian flow, whose source is just left of the center of the bottom edge of the picture, split into two forks when it reached the central pumice cone. One fork flowed left into East Lake, the other right into Paulina Lake. The north pumice cone with its perfectly formed crater lies just to the right of the vent that fed the interlake obsidian flow. The Big Obsidian flow occupies the upper right corner of the picture. Two steps in the south caldera wall can be seen, one behind the source, and the other left of the Big Obsidian flow. (Oregon Dept. of Geology and Mineral Industries photograph)

Fig. 10. The Big Obsidian flow occupies the central part of the view. Behind it lies the curving southwest wall of the Newberry caldera, emphasized by a dusting of new-fallen snow. The stepped nature of the caldera rim can be clearly seen. In the background numerous cinder cones dot the south slope of the Newberry shield. Little Crater tuff ring is in the left foreground on the shore of Paulina Lake. Above it a lobe of the Big Obsidian flow has overtopped and nearly filled the crater of the south pumice cone. (Oregon Dept. of Geology and Mineral Industries photo)

Big Obsidian flow

The largest, and most spectacular, of the Newberry obsidian flows issued near the south rim of the caldera and spread as a broad lobate tongue for about a mile and a half towards the center of the caldera (figs. 7, 9, 10, and 11). Its front stopped just short of the Little Crater tuff ring. Absence of air-fall pumice on the Big Obsidian flow indicates that it formed later than the pumice cone activity. Although the lack of vegetation makes it possible that this flow is younger than the interlake flow, the differences in vegetation may only reflect differences in availability of water to the two flows. The position of the interlake flow between the two lakes, essentially mounted on East Lake's underground drainage, may be one cause of its thicker vegetation.

The blocky surface of the obsidian flow is diversified by ridges 10 to 15 feet high and 20 to 30 feet apart. They consist of jumbled blocks of grayish partly-frothed obsidian. In troughs between the ridges blocks of lustrous black obsidian have been brought up from beneath the frothy flow top by ramps that extended into the pasty lava below. On the sides of the flow these swales and ridges have been pulled, squeezed, and autobrecciated into closely spaced ridges parallel with the flow margin.

The last event in the development of the flow was the rise of a dome of obsidian. It projects out of the vent to a height of 20 to 60 feet above the flow surface, forming a deeply fractured and jagged-topped spine (fig. 12).

Other features

Other volcanic features and flows present on the caldera floor are still being investigated and will not be discussed in this paper.

Post-Caldera Faulting

In addition to the post-caldera movement on ring fractures already mentioned, other faults have significantly modified the caldera and the shield since caldera formation. Some of these faults are only recognizable by the alignment of cones on them, or of flows from them. Others have scarps and show displacement of flows.

Fig. 11

Fig. 12

Fig. 11. The central part of Newberry caldera, looking northeast. The low but broad crater of the Little Crater tuff ring is in the center of the view, just to the left of the interlake road. Most of the bulk of this underwater volcano is below the level of the lakes. Steep-sided central pumice cone rises behind Little Crater. The front of the main lobe of Big Obsidian flow rises 60 feet above the timbered pumice plain in the right foreground. Across the caldera, near the upper north corner of the photograph, the source of the interlake obsidian flow can be seen at the foot of the north wall of the caldera. This obsidian flow, central pumice cone, and Little Crater tuff ring form the land bridge that divided a former large caldera lake into Paulina Lake (left foreground) and East Lake (center background). (Oregon Dept. of Geology and Mineral Industries photograph)

Fig. 12. A low plug dome with a fissure across its left edge marks the final stage in the development of the Big Obsidian flow. (Oregon Dept. of Geology and Mineral Industries photograph)

Still others can be recognized only by displacement of the stratigraphic sequence in the caldera walls.

North-south trending faults

Williams (1935, p. 268) first suggested that downfaulting might be the cause of the absence of a wall on the west side of the Newberry caldera. The evidence we have accumulated indicates that this is indeed the case.

Contrary to Williams' tentative correlation, however, the andesite and olivine-poor basalt overlying the mafic graded tuff at Paulina Falls (the upper falls) does not match anything on the caldera walls. Andesites on top of the east wall of the caldera are post-caldera in age and were erupted from late ring fractures, whereas the andesite and olivine-poor basalt at Paulina Falls is pre-caldera in age and was erupted from one of the central vents.

On the other hand, the platy andesite cropping out at the lower falls on Paulina Creek does correspond to the platy andesites in the caldera walls, and the mafic graded tuff overlying the platy andesite along Paulina Creek between the lower and upper falls (Paulina Falls) corresponds to the mafic graded tuffs overlying the platy andesites in the caldera walls.

One major fault (although possibly not the only fault involved which accounts for this downthrow of the western wall) trends north-south across the caldera. It extends through the Red Slide on the north wall above Paulina Lake, and intersects the south wall just east of Paulina Peak, where, however, its exact position is obscured by the fact that the Paulina Peak rhyolites probably rose through a vent or vents developed at the intersection of this fault with the fault defining the rim of the caldera. The evidence for the existence of this fault is as follows:

1. The stratigraphic sequence (rhyolites, platy andesites, red scoria, and mafic graded tuffs -- present in both north and south walls of the caldera) ends abruptly at this fault, but it is found again (same sequence, identical rocks) in the valley of Paulina Creek. The stratigraphic throw of corresponding stratigraphic units on the two sides of the fault amounts to 400 to 600 feet.

2. North of Paulina Lake the fairly even top of the caldera wall drops abruptly about 200 feet in elevation just west of the Red Slide, reaching the level of the west rim in half a mile. On the south wall of the caldera, however, this is not the

case, for Paulina Peak, the highest point on the caldera rim, lies just west of the supposed fault line. Just east of where the fault is believed to cut the south wall of the caldera, the rhyolites, platy andesites, red scoria, mafic graded tuffs, and brown scoria of the pre-caldera sequence, which have maintained a fairly constant dip, causing them to appear as nearly horizontal layers on the wall as they are followed from east to west, are bent downward toward the west. In the next outcrop to the west of this bend the younger rhyolites of Paulina Peak occupy the steep face of the wall in place of the pre-caldera sequence, and are continuous clear to the level of the caldera floor. The exact junction of the pre-rhyolite units with the younger rhyolite is covered by a talus slope, hence the fault itself is not visible. Our interpretation of this relation is that the rhyolites forming Paulina Peak were erupted concurrently with or shortly after, the western block began moving down along this fault. Thus the intersection of the north-south fault with the ring fault of the caldera probably determined the location of the vent, or at least one of the vents, from which the rhyolite erupted. The fact that the younger rhyolite extends to the caldera floor suggests that it may have filled a valley formed by the faulting.

3. The alignment of other volcanic features along this fault scarp appears to be more than coincidental. Among them are cinder cones on both the north and south slopes of the shield.

4. Although he did not attribute the downdropping of the western part of the caldera to a large fault at this particular line, Williams (1935, p. 271) recognized a break through the Red Slide on the north wall of the caldera. He wrote: "These cones, known locally as the 'Red Slide', apparently lie on a north-south fissure, which opened downward as activity progressed, for the latest outflow was a short stream of basalt that escaped from near the base of the younger cone."

5. Numerous faults with less displacement parallel this line. They can be seen on both the north and the south walls of the caldera; a few have displacements of as much as 100 feet. Also troughs and elongate cones or spatter ridges with north-south trends are discernable on the contour map of the bottom of East Lake.

Northwest-southeast trending faults

Many northwest-southeast alignments are noticeable on the Newberry shield. This structural trend is also common within the caldera. The most visibly continuous of the northwest-southeast trending faults is locally known as "The Fissure." This fault is seen as an open scar on the north wall above the northwestern corner of East Lake. It can be traced, though, with numerous small en echelon offsets, from the water's edge at East Lake to several miles northwest of Lava Butte, a total distance of more than 30 miles. It is an open fissure where crossed by U.S. Highway 97 near the southeast corner of Lava Butte. From the fissure numerous flows have been erupted (Peterson and Groh, 1965, p. 9). It has been stated that the fissure extends south of East Lake to Devils Horn, but this is in error; Devils Horn is on one of the north-south lineaments.

Displacement of the stratigraphic units by this fault on the north caldera wall probably amounts to 200 to 300 feet. The eastern block dropped down relative to the western block. This displacement is one factor that accounts for the occurrence of the platy andesite, instead of the older rhyolite, along the base of the east wall of the caldera. This downfaulting may also have lowered the east rim enough to provide the trough that channeled the ash flow which formed the welded tuff. If so, the fault was active just before the caldera collapse. It also has been active since the caldera was formed, as shown by fountaining of basalt scoria out of this fissure to form spatter ramparts upon its rims near the northwestern corner of East Lake, and by lava flows that emerged from it at several points on the northwestern flank of the shield.

Relations of the north-south faults to the northwest-southeast faults

Although the junctions between the north-south faults and the northwest-southeast faults have not been observed directly in the field, the nature of their meetings as seen on aerial photos, and particularly the nature of their intersections shown on the bottom contour map of East Lake, indicate that the two trends belong to the same system. Instead of two intersecting fault systems, it is believed that these two trends represent one contemporaneous set of faults bending sharply or splitting off from north-south trends to northwest-southeast trends, just as the Brothers Fault Zone bends in this region.

Northeast-southwest trending faults

Many small (both in the sense of length,-width, and displacement) faults with northeast-southwest trends are also discernible in the Newberry Volcano, particularly in the caldera. These faults generally appear as enlarged joints on which small displacements have occurred. They never account for major offsets of strata or of the topography of the walls, and probably they represent slight adjustments to recent movement of old faults beneath the caldera floor. Nevertheless this is the trend of the prominent Walker Rim fault, which has a displacement of more than 1500 feet. The Walker Rim fault gradually decreases in throw to the northeast before it disappears beneath the young lavas on the southern rim of the Newberry shield.

Differentiation at Newberry Volcano

Newberry Volcano has been cited as a good example of the so-called "basalt-rhyolite association" (Williams, 1935, p. 300-303; Turner and Verhoogen, 1960, p. 279, 286-287) because it was thought that here large volumes of mafic lavas and silicic lavas were present, with a paucity of lavas of intermediate composition. Pending thin sectioning of hundreds of inclusions collected from many cones and flows on the caldera floor and on the shield, little can be said about the rocks that make up the huge unexposed bulk of the shield. From the rocks exposed on Paulina Creek and in the caldera walls, however, it appears that intermediate lavas are perhaps nearly as voluminous as the more mafic and siliceous varieties. Platy andesites and andesite tuffs are prominent components of the caldera walls and of parts of the shield; they appear to show gradations toward both the basalts and to the less siliceous of the "rhyolites." Platy olivine andesites are the chief shield-forming lavas of the Medicine Lake Highlands (Anderson, 1941), an area which has many similarities to the Newberry Volcano.

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PAISLEY CLAIMS LEASED TO HANNA FOR EXPLORATION

Exploration of 83 claims south of Paisley in Lake County as a potential area for minerals development will be undertaken by the Hanna Mining Co. of Cleveland, Ohio, under terms of a memorandum of option agreement signed by that firm and owners of the claims, it was announced by Ross Foster, one of the principal owners. The site is along the face of the mountain south of Paisley, and involves an area about three miles long and more than a mile wide. Foster said minerals included copper, gold, lead, zinc, silver, and mercury.

Together with Con O'Keeffe of Twin Falls, Idaho, a Westside rancher, and Kenneth Faulk of Lakeview, he has been prospecting, staking, and exploring the Paisley region for about two years and has an interest in most of the claims and claim groups leased to Hanna. Others involved in claim ownership are Coy Amacker, Don Tracy, Don Fitzgerald, Ross Colahan, Bertron Daron, Paul DuBose, and their families.

The lease, filed with the Lake County Clerk February 27 by Attorney T. R. Conn, provides for the agreement to expire December 31, 1969, unless continued by other agreements. (Lake County Examiner, March 2, 1967)

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