UNIVERSITY OF CALIFORNIA
Santa Barbara

Tuff Rings of the Fort Rock - Christmas Lake Valley Basin
South-Central Oregon

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Geology

by

Grant Harvey Heiken

Committee in charge:

Professor R. V. Fisher, Chairman

Professor C. A. Hopson

Professor R. M. Norris

Professor W. S. Wise

Professor W. C. Walker

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VITA

October 11, 1942--Born--Monticello, Iowa.

1964--B.A., University of California, Berkeley.

1964-1966--Research and teaching assistant, Geology Department, University of Texas.

1966--M.A., University of Texas, Austin.

1966-1969--Teaching and Research Assistant, University of California, Santa Barbara.

1969-Present--Geologist, Planetary and Earth Sciences Division, NASA Manned Spacecraft Center, Houston, Texas.

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ABSTRACT

TUFF RINGS - EXAMPLES FROM THE FORT ROCK - CHRISTMAS LAKE VALLEY BASIN, SOUTH-CENTRAL OREGON

by

Grant Harvey Heiken

Tuff rings are wide, low-rimmed, well-bedded accumulations of hyaloclastic debris built around volcanic vents located in lakes, coastal areas, marshes and areas of abundant ground water. Tuff rings within the Fort Rock - Christmas Lake Valley Basin were erupted during Plio-Pleistocene time into a lake that occupied the basin. Outside the lake basin are related cinder cones and flows. The cinder cones and tuff rings occur along faults that cross the basin and adjacent highland. The shape and height of the tuff rings appears to be dependent, in part, on the depth of explosive steam generation when rising magma came into contact with ground or surface water (phreatomagmatic eruptions).

Eruptions within the lake produced underwater debris flows which deposited massive tuff-breccia now exposed at the bases of the tuff rings. Once the rings breached the surface, much of the ash was deposited from the air to form thin beds showing bedding plane sags ("bomb sags"). Some subaerial beds were deposited by base surges (as at Taal, Philippines, 1965) which formed radial dunes and

abundant cross-bedding, and, in places, plastered ash onto slopes of 45 to 90 degrees. When the eruption ceased before the flow of water into the vent stopped, the vents were filled with concentric, vertical tuff beds and massive tuff-breccia. When the flow of water into the vent ceased before the eruption stopped, craters were partly filled with cinders, spatter, and small lava lakes.

Hyaloclastic ash of basaltic composition makes up about 95% of the ejecta in these tuff rings. Most of the ash consists of clear, light brown to medium brown glass fragments, containing only a few microlites in addition to phenocrysts. Generally the grains have a blocky shape and low vesicularity, in contrast with the curved, highly vesicular droplets, bombs, and cinders of cinder cones outside of the lake basin which were contemporary with the tuff rings. The hyaloclastic grain morphology is the result of contraction and shattering when the magma was quenched to glass on contact with water.

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INTRODUCTION

A tuff ring is a small volcano characterized by a very wide crater and a low ejecta ring. Tuff rings consist primarily of juvenile ejecta, in contrast to explosion craters, which are constructed primarily of debris from the crater. Water apparently had access to the vents during the eruptions that formed the tuff rings; most tuff rings are found in lakes, coastal areas, marshes, and areas of abundant ground water. The characteristics of the volcanoes located in the Fort Rock - Christmas Lake Valley basin were studied to determine the role of surface water in their genesis.

Geography

The Fort Rock - Christmas Lake Valley Basin is the northernmost of the major pluvial basins of the Basin-Range Province (Morrison, 1965)(fig. 1). This broad depression is about 40 miles (64 km) long and 25 miles (40 km) wide. Faulted late Tertiary plateau basalts rim the basin. Only volcanic features and aeolian blowouts break the flat surface of the valley floor.

Oregon State Highway 31, which branches off U. S. Highway 97, 32 miles (51 km) south of Bend, Oregon, skirts the west edge of the basin. The highway and numerous dirt roads provide access to all parts of the basin. The adjacent mountainous areas are accessible via Jeep trails. Three small settlements, Silver Lake, Fort Rock, and Christmas Valley are supported by cattle ranching, timber and tourism.

Average annual precipitation is less than 10 inches (Hampton, 1962). Water wells reach down to good aquifers in plateau basalts. Surface water occurs at Paulina Marsh and Silver Lake, which are fed by Buck, Bridge and Silver Creeks. Christmas Lake is dry.

West of the basin, hills are covered with sagebrush, juniper, and ponderosa pine. Farther west and at higher elevations the forests change to a variety of conifers.

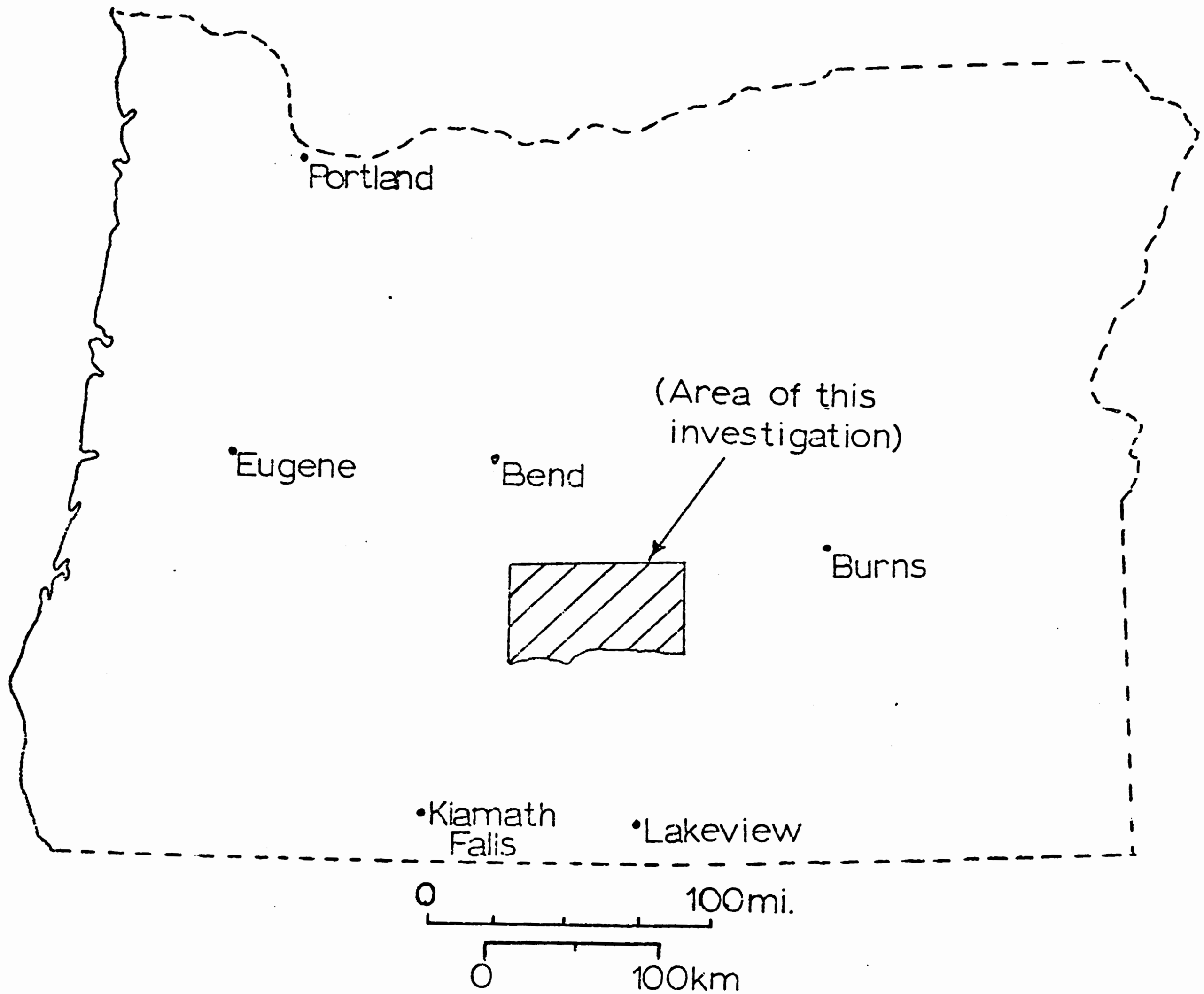


Fig.1. Map of Oregon.

Within the basin only sparse sagebrush and clumps of grass survive. No trees grow on the lake sediment, except at Lost Forest (fig. 2) where ponderosa pines grow in wind blown sand above a perched water table.

Tuff rings are easily recognized; they occur as brownish-orange hills and ridges rising above the basin floor, and are commonly covered with junipers.

Previous Work

Allison (1966) has summarized the findings of numerous paleontological expeditions to Fossil Lake, in eastern Christmas Lake Valley.

The structure, especially the fault pattern, has been studied by Russell (1884), Donath (1962), and Hampton (1964). Walker, Peterson, and Green (1967), published an excellent geologic map.

Water supplies are discussed in papers by Russell (1884), Van Winkle (1914), and Hampton (1964). Russell recognized that Christmas Valley is a former lake basin. Recent studies are by Hampton (1964), and Allison (1966). Dole (1941, 1942) described lake sediments and ash exposed in aeolian blowouts at Fossil Lake.

Studies of nearby volcanic features include a structural investigation of Glass Buttes by Waters (1927), geologic mapping of Newberry Caldera by Williams (1935), and Higgins and Waters (1967, 1968). Tuff rings in the

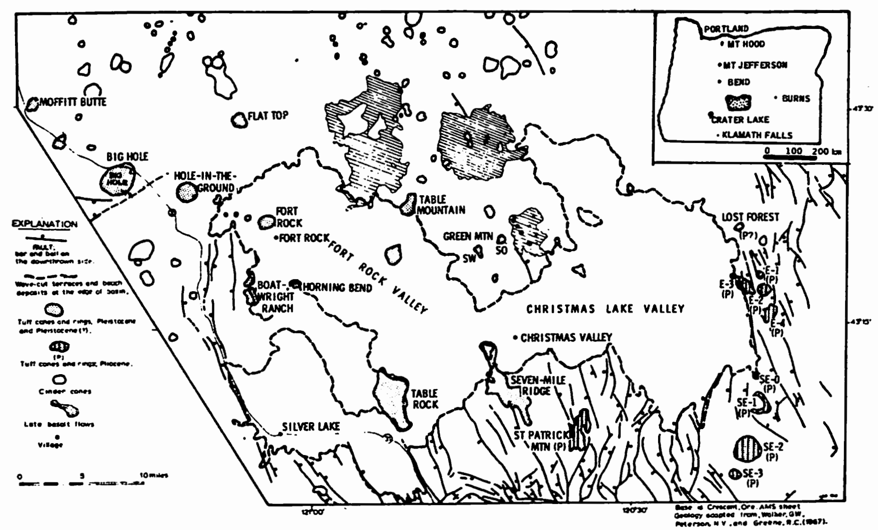


Fig. 2. Index map of the Fort Rock - Christmas Lake Valley Basin, showing location of investigated tuff rings and cones, (after Walker, G. W., Peterson, N. V., and Greene, R. C., 1967).

basin are briefly described by Peterson and Groh (1963) and Waters (1967).

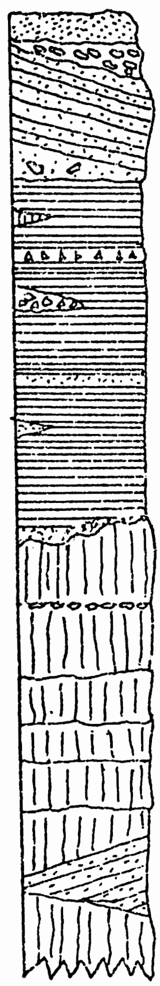
Methods and Procedures

I mapped the tuff rings of the Fort Rock - Christmas Lake Valley basin in 4 months during parts of 1967, 1968 and 1969. Mapping was done on 1:24000 scale aerial photographs taken by the U. S. Department of Agriculture, Soil Conservation Service. I compiled the planimetric maps at a scale of 1:8000, using enlargements of selected photographs. The location map (fig. 2) was compiled from the 1:250000 scale Crescent AMS Sheet and a geologic map by Walker, et al. (1967). Stratigraphic sections were measured using a Jacob's staff and Brunton compass.

Chemical analyses of the tuffs and lavas were made by x-ray flourescence techniques as outlined in UCSB Geology Department Information Circular no. 1 (unpublished ms., 1967). Samples analyzed were powdered and pressed into pellets. The standards used were U. S. Geological Survey silicate rock standards G-1, W-1, and AGV-1. Na_2O was analyzed by flame photometry. H_2O was analyzed by techniques outlined in Shapiro and Brannock (1962).

Stratigraphy of the Fort Rock - Christmas Lake Valley Basin

Deposits in the Fort Rock - Christmas Lake Valley range in age from Pliocene to Recent (fig. 3). The oldest formation in the area is the Pliocene Picture Rock Basalt



Age	THICKNESS (METERS)	DESCRIPTION
PLEISTOCENE AND RECENT	0-9.5	Sand dunes at the eastern end of Christmas Lake Valley.
	0-2.0	Gravels eroded off the tuff rings.
	0-215	Tuff rings and cones of partly palagonitized sideromelane tuff.
?	0-215	Lake sediments; mostly diatomite. There are some interbedded tuffs and sandstones. Near the basin edge and interbeds of coarser grained sediment and lava flows.
PLIOCENE	230+	Flows of highly feldspartic basalt with a diktytaxitic texture. The Picture Rock Basalt of Hampton (1964). There are some interbedded tuffaceous sediments and basaltic tuffs exposed along the southeast edge of the basin.

Fig. 3. General stratigraphic column of the rocks in the Fort Rock - Christmas Lake Valley Basin, based on measured sections and driller's logs (from water wells; Hampton, 1964).

(Hampton, 1962). The formation is over 230 meters thick and consists of thin basalt flows which form the basement beneath the lake deposits of the Fort Rock - Christmas Lake Valley Basin. It is well exposed in the east wall of the Silver Lake Graben. Here, individual flows about 9 meters thick dip gently under the younger deposits, forming the main aquifer of the basin. Subophitic and diktytaxitic groundmass textures of the basalts are spotted with abundant phenocrysts of labradorite and sparse olivine rimmed by iddingsite (Walker, Peterson, and Greene, 1967).

In places, thin flows of the Picture Rock Basalt are interbedded with conglomerates, sandstones, and tuffaceous mudstones, interpreted by Walker, Peterson, and Green (1967) as floodplain or shallow lake deposits. These sediments extend beyond the southeast edge of Christmas Lake Valley and into the northern end of Fandango Canyon. Fossils collected from the interbedded siltstones 4 km south of Buffalo Wells are of Hemphillian age (middle Pliocene) (Walker, Peterson, and Greene, 1967). Interbedded with the sediments and basalts are hyaloclastite beds of the oldest tuff rings in the area which are exposed around the southeast edge of the basin (tuff rings SE-0, 1, 2, and 3, E-1, 2, 3, and 4, and the St. Patrick Mountain-Fandango Canyon complex; see fig. 2.

Tuff rings at Table Rock, Seven-Mile Ridge, Fort Rock, Table Mountain, and Horning Bend (fig. 2) overlie flat lying lacustrine sediments and interbedded tuffs. As determined from drillers' logs of water wells (Hampton, 1962, pp. B-24 to B-27), the lacustrine sediments and tongues of basaltic tuffs, probably derived from the tuff rings, range in thickness from zero at the southern basin edge to over 220 meters under Table Rock.

The uppermost lake beds, well-exposed under the west edge of Table Rock (fig. 2), consist of interbedded, moderately well-sorted sandstones (volcanic litharenites and lithic arkoses[1]), diatomaceous siltstones, and white lapilli-tuff (appendix 1). The sandstones consist of subrounded to angular grains of basalt, plagioclase, augite, basaltic and rhyolitic ash, claystone, and siltstone. Some of the well-bedded sandstones are cross-bedded, with indicated current directions oriented eastward into the basin. The source of the sands is the Connley Hills in the Central-western part of the basin, which are a line of basaltic cones and intermediate to silicic domes and flows. This group of volcanic hills appears to have been an island, about 6.4 km wide and 19 km long, throughout the

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[1]Sandstone terminology is that of Folk (1968).

history of the basin. Wells drilled close to the ridge (well log 8, appendix 1) penetrated lava flows and volcanic breccias, interbedded with sediments generally coarser grained than those in the central part of the basin (well log 9, appendix 1). A basalt flow is interbedded with sediments which crop out below Table Rock. (Cross section C-C', plate 15).

The contact between diatonaceous sediments and palagonite tuff breccia of Table Rock is sharp. There is no gravel, talus or soil on the uppermost lake sediments. Rapid deposition of thick basal tuff breccias of tuff ring 2, Table Rock, deformed the underlying sediments (fig. 5). Sediments cropping out under the tuff-breccia at this location dip under the ring at angles of 30 to 40 degrees. This is abnormal; away from Table Rock and in the basin, the sediments are flat-lying. Some of the highest beds have been injected into the tuff-breccia as mudstone dikes (fig. 4). The dikes have sharp, irregular boundaries and bulbous, ovoid, and sheet-like shapes. Thicknesses vary from less than 2 cm to 3 meters in diameter. A single dike may have a narrow connection with sediments underlying the tuff-breccia, broaden into an oval shape, then narrow to a point.

The sediments below tuff rings at Table Rock behaved plastically and retained bedding features during

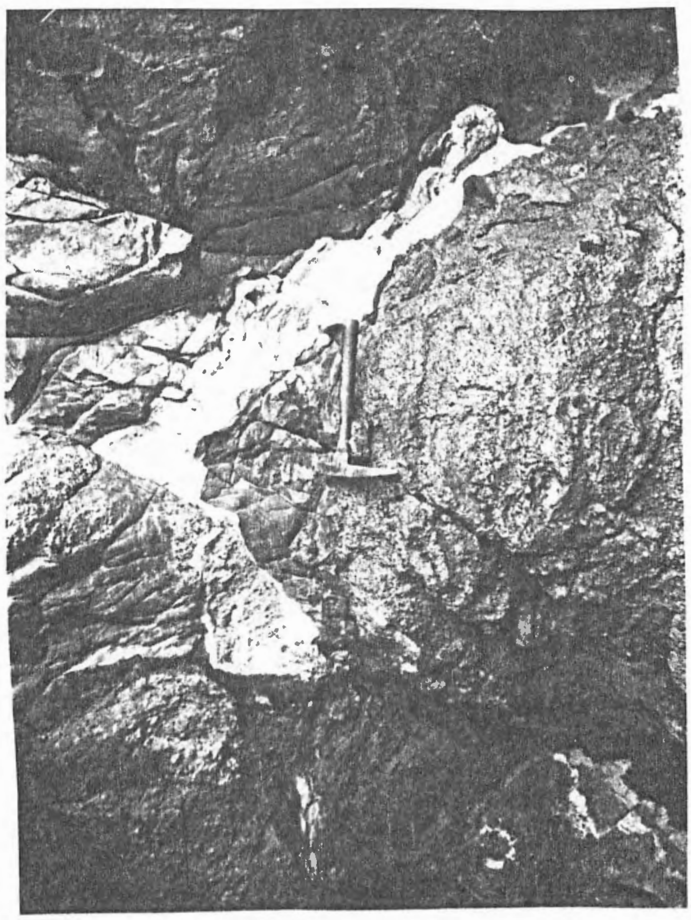


Fig. 4. Mudstone dike in massive tuff-breccia of tuff ring #2, Table Rock tuff ring complex, located about 2.5 meters above the tuff-breccia lake sediment contact.

injection into the tuff-breccia (fig. 5). One meter below the tuff-breccia lake-sediment contact, the sediments are deformed by small-scale faulting and fracturing rather than plastic movement. The topmost layers, deformed in a plastic manner, were probably water-saturated and less well-consolidated than those below them.

The northern part of Seven-Mile Ridge (fig. 2) is underlain by finely-laminated diatomite, with interbedded silicic pumice and a few thin beds of basaltic tuff. The best exposed section of these sediments is at the junction of Wagontire road where a dry wash drains the western slope of the ridge (fig. 9). About 2.4 kilometers west of the ridge, diatomite is mined commercially in open pits.

Reversely graded beds of silicic pumice, interbedded with the diatomite, are 12 cm to 30 cm thick. They are graded from tuff size to lapilli 3 cm in diameter. Reverse grading of pumice indicates deposition in standing water (Fiske, 1969).

The southern edge of Table Mountain overlies a well-preserved beach deposit which is 1.5 kilometers long and 300 meters wide. It consists of well-sorted, well-rounded obsidian gravel and sand derived from the erosion of Cougar Mountain, an obsidian dome 1 km west, and transported east by longshore drift.

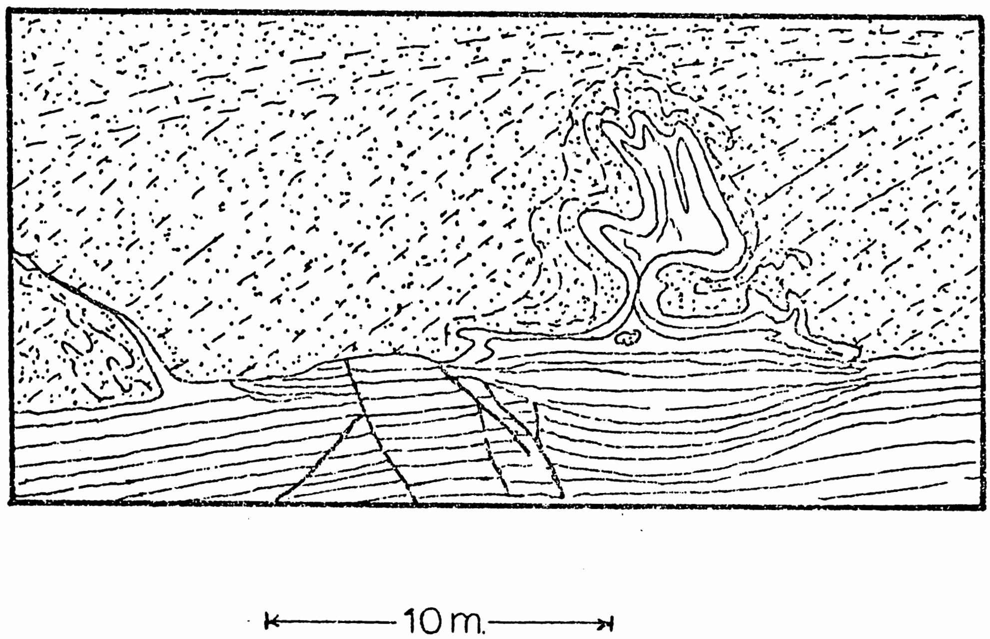


Fig. 5. Diagram of deformation pattern at the tuff-breccia (stippled) - sediment (plain) contact, below tuff ring #2, Table Rock tuff ring complex. Uppermost layers of sandstone and mudstone are intruded into the basalt tuff-breccia as dikes. Deformed bedding planes are preserved within the dikes, although nearly pinched off where the dike enters the breccia. Bedding below the contact is also deformed by small scale faults.

Sediments directly under Fort Rock and under the tuff ring south of Table Mountain (fig. 2) are covered by talus and alluvium. Well logs from two wells drilled between the two rings (8 km east of Fort Rock and 8 km west of the tuff ring south of Table Mountain) penetrate about 70 meters of clay (diatomite), sand,and tuff.

Palagonite tuffs from the vent at Horning Bend (fig. 2) overlie the talus-covered slopes of a dacite dome and extend out over lake sediments which surround and lap up against the dome.

Sediments exposed in aeolian blowouts at Fossil Lake are similar to those below Table Rock and Seven-Mile Ridge. Dole (1941) describes these sediments as mostly diatomite with interbedded silicic pumice and ashy sand. Allison (1966) describes the mid-Wisconsin age fauna at Fossil Lake. Lake sediments at Four-Mile Blowout contain fossils of indefinite mid-Pliocene age (George Walker, pers. commun., 1968) Hampton (1962) calls the sediments exposed under Seven-Mile Ridge Pliocene, on the basis of 28 species of diatoms, seven of which are extinct.

Hampton (1962) correlates the lake sediments and overlying tuff rings, which he calls the Fort Rock formation, with the Yonna Formation of the Klamath Basin. Such correlations, based only on lithologic similarities are not valid; on such a basis the rocks could be correlated with basaltic tuffs of any age.

A wave-cut terrace at an elevation of about 1336 meters is visible along the edge of the basin (fig. 2). It is best seen against steep slopes which border the southeastern part of the basin. Table Rock, Seven-Mile Ridge, Fort Rock, Table Mountain, a tuff ring at Boatwright Ranch, (fig. 2) and the tuff ring south of Table Mountain are notched by wave-cut terraces at the same elevation. Northern Seven-Mile Ridge and the tuff ring south of Table Mountain were completely leveled by wave action, leaving mesas 8 to 15 meters above the floor of the basin.

Sediments in the Fort Rock - Christmas Lake Valley Basin were deposited in a lake during Pliocene and Pleistocene time. Evidence for a lake includes: 1. The presence of diaomite in wells and in sections under Table Rock, Seven-Mile Ridge, Fort Rock, and the unnamed tuff ring south of Table Mountain; 2. Reverse-graded pumice beds in the diatomites; 3. Fossil fish and water birds at Fossil Lake; 4. A beach deposit underlying Table Mountain; and 5. A wave-cut terrace bordering the basin.

GENERAL DESCRIPTION OF TUFF RINGS

TABLE ROCK TUFF RING COMPLEX

Introduction

Table Rock is a tuff cone located about 9 miles (14.5 km) east of the village of Silver Lake, and is a part of a tuff ring complex consisting of two large tuff rings (numbers 1 and 2), the Table Rock cone (number 3), and six small vent areas with or without rings (numbers 4 to 9). The deposits of the complex form an elongate oval, 5.6 by 8.8 kilometers, with the long axis oriented NNW by SSE (pl. 1). The highest point, about 395 meters above the surrounding plain, is the crest of the flat topped Table Rock.

A normal fault defining the steep eastern wall of the Silver Lake Graben to the south, is directly in line with the long axis of the complex and probably lies beneath it. The fault, however, was not observed to cut the layers which form the complex.

Tuff Ring 1

Erosional remnants of tuff ring 1 consist of two crescent-shaped ridges forming an oval 2300 meters by 2700 meters. Both ridges rise about 95 meters above the lake basin floor. They partly enclose a nearly flat area composed of tuff and tuff-breccias which is 2 meters to 12 meters above the lake basin floor.

The ring is composed of palagonitized sideromelane tuff, lapilli-tuff, and tuff-breccia. They form generally brownish-gray slopes around the outer flanks and ridge tops and orange-brown slopes near the center. Tuffs and lapilli-tuffs around the flanks of the ring occur in uniformly thick beds 1 cm to 2 m thick. In the crater area, however, bedding is poorly preserved. Bedding which is distinct along the flanks of the ring gradually "fades" into massive palagonite tuff in the crater area.

Bedding is deformed in some parts of the tuff ring by slumping and convolute-type bedding on the inner and outer slopes as well as along the crest of the ring. A sequence of penecontemporaneously folded tuff beds, 6.1 m thick, is located near the crest of the ridge on the east side of the ring. There, the tuff beds are deformed into broad, low-amplitude folds which are over and underlain by undeformed tuff beds dipping toward the center of the ring at an angle of 15 degrees. The contact with the underlying tuffs is sharp and may have been a glide plane along which the tuffs slid. The deformed beds are similar to convolute bedding; defined by Kuenen (1953) as a structure characterized by crumpling or folding of laminations within a well-defined sedimentation unit.

At the southern end of tuff ring 1 is an outcrop where the 61 m thick sequence of tuff beds has been folded into a steep, overturned anticline (fig. 6a). The contact with undeformed beds under the folded beds is sharp; the undeformed beds and glide plane dip outward from the crater area at an angle of 6 degrees. The sliding may have occurred following the inward slumping of tuff beds as shown in figures 6-b, c, d.

The bedding along the northern edge of the ring is cut by a channel which has the shape of a flattened "U" in cross section. It is 30 meters wide and 6 meters deep, and is filled with beds of sideromelane tuff and lapilli-tuff which drape over the channel walls and extend beyond them. The channel is oriented normal to the ring crest; the channel floor plunges outward, from 9 degrees at the crest, where it cross-cuts flat tuff beds to 20 degrees down the outer slope of the ring. The channel may have been a gully cut by running water between different phases of the eruption which formed the tuff ring.

Tuff Ring 2

Tuff ring 2 consists of a circular ridge about 4000 meters in diameter and 120 meters high at the present crest. The crater floor is approximately 2100 meters in diameter and 30 to 75 meters below the ridge crest. The southern edge of tuff ring 2 is partly covered by the tuff cone 3 (Table Rock). Part of tuff ring 2 crops out on the south side of the tuff cone 3.

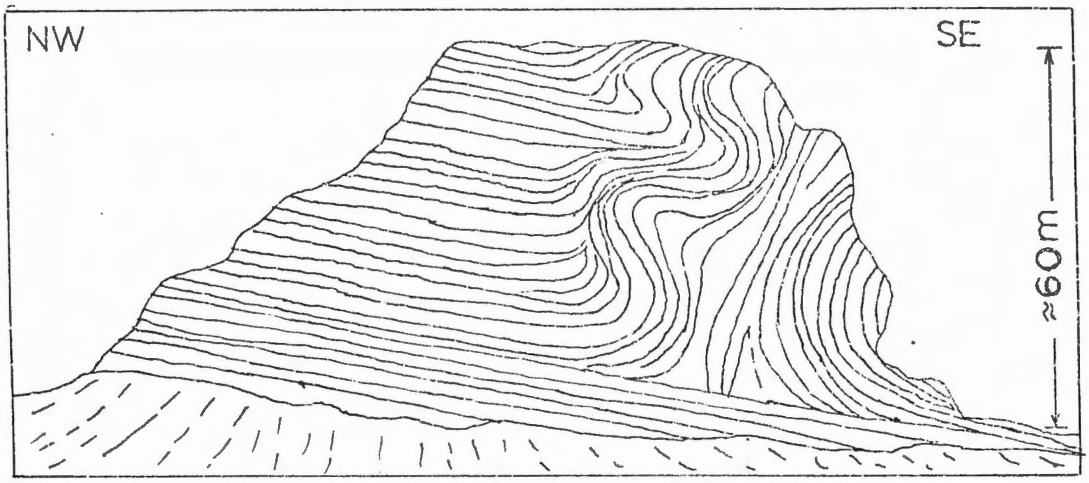
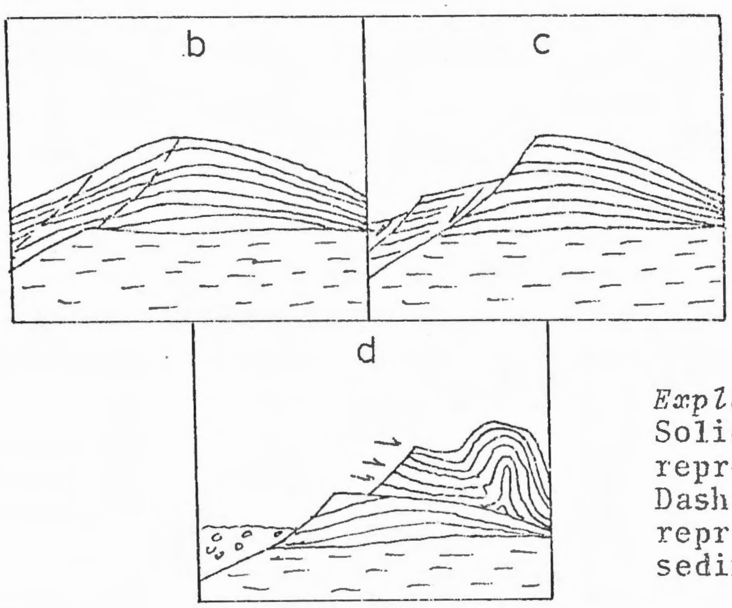


Fig. 6-a. Slump Structure in bedded tuff on the east edge of Tuff Ring 1, Table Rock.

Figs. 6-b, c, d (below). Diagrams illustrating the history of events leading to the formation of the slump illustrated in fig. 6-a.



Explanation:
Solid lines represent tuff. Dashed lines represent lake sediment.

b. Formation of anticline-like structure typical of tuff rings by deposition of tuffs during eruption(s).
c. Masses of bedded tuff slump into the crater.
d. Unstable tuff remaining on the outer flank of the ring slides toward the southeast along a more competent detachment horizon.

Wave erosion has carved a terrace and cliffs up to 45 meters high into the eastern and northern slopes of the ring. The north end of the ring is breached by a pass about 150 meters wide, where drainage from the crater to the lake is blocked by a lake-deposited gravel bar which consists of well-rounded cobbles and pebbles of palagonite tuff (fig. 7).

The beds which comprise the tuff ring are composed of yellowish-brown to gray-brown tuff, lapilli-tuff, or tuff-breccia. Tuff-breccia exposed at the base of the ring is massive, and in beds a meter to over 15 meters thick; these beds are best exposed along the Christmas Valley Road on the west side of the tuff ring. Higher in the ring, the rocks tend to be more thinly bedded, ranging from 0.8 cm to 2.5 m thick. Bedding thicknesses are very uniform and in some places can be traced for hundreds of feet without thinning or thickening. Graded bedding is common.

Sedimentary structures which show current directions are present nearly everywhere around the rim of the tuff ring. Simple, tabular cross-bedding is most common with bed thicknesses of 2 cm to 60 cm. Exceptions are the large cross-beds visible in the basal tuff-breccia on the west side of the tuff ring (fig. 5); these are 6 to 9 meters thick. On the inside slope of the northeastern

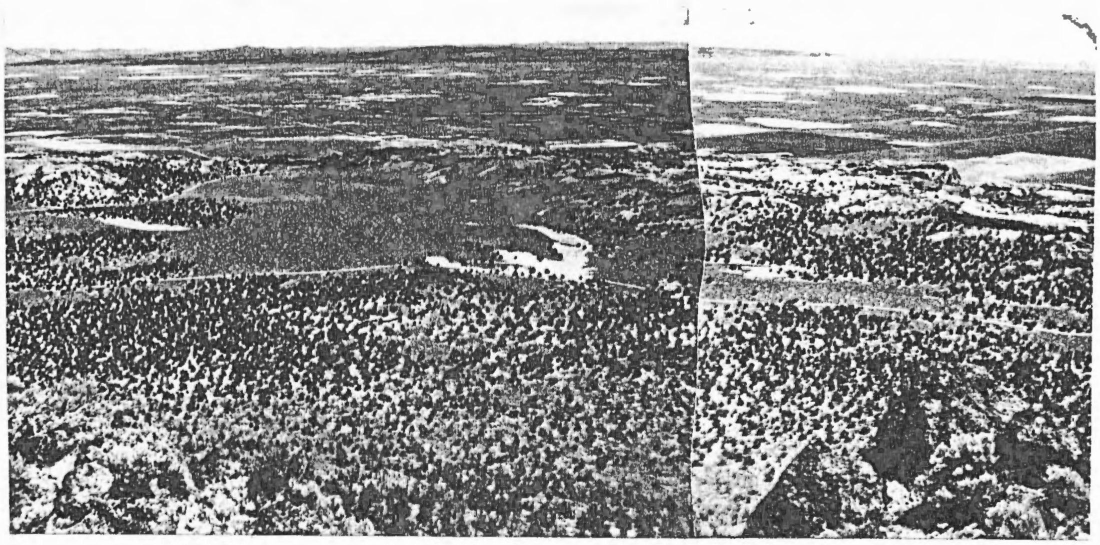


Fig. 7. Northern and eastern parts of tuff ring 2, Table Rock tuff ring complex. Photo taken from the top of Table Rock. The Fort Rock - Christmas Lake Valley Basin makes up the plain in the middle and far horizon.

The light-colored, barren ground near the center of the photograph is located near the center of the tuff ring.

part of the ring are several sets of dunes; the average distance from crest to crest being 2 m and the average dune height 0.6 m (fig. 8). Measurements of the cross-beds within these dunes indicate that the depositing currents moved upslope out of the crater and radially away from its center.

Bedding plane sags (depressions in well-bedded tuff and lapilli-tuff) are common; each sag was formed by a basalt block which impacted into poorly consolidated ash beds after being ejected from the crater.

Channels are cut into bedded tuff on all sides of the tuff ring. Twenty-three channels were mapped (plate 1); these are located mainly on the outer slopes of the ring, oriented normal to the ring crest. All have 'U' - shaped cross-sections and are 1 to 21 m deep and 2 to 30 m wide (fig. 9). The original lengths of the channels could not be determined, but several were traced for about 150 m. Most of the channels appear to have been gullies cut by running water between different phases of the eruption which formed the ring. Most of the channels were evidently cut before the bedded ashes in the ring were cemented, as suggested by the absence of cobbles or pebbles of cemented palagonite tuff within the beds of these ancient gullies. Well-bedded sideromelane tuff and lapilli-tuff fill the channels and drape over the sides. The beds are usually

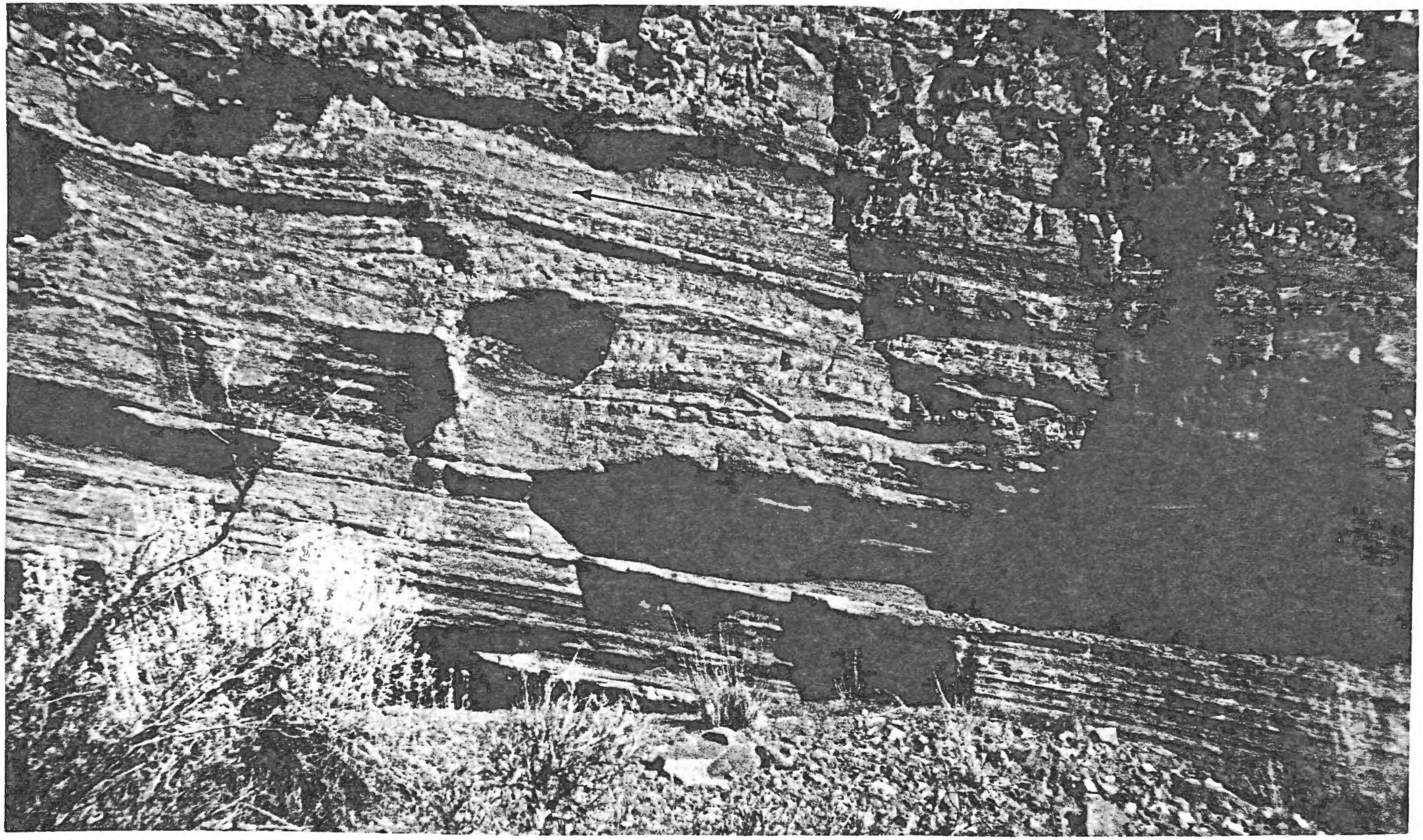


Fig. 8. Dunes, interbedded with the plane beds of the eastern rim of tuff ring 2, Table Rock tuff ring complex. Undeformed beds dip in toward the crater at an angle of 9 degrees. The arrow shows current direction as indicated by cross-bedding.

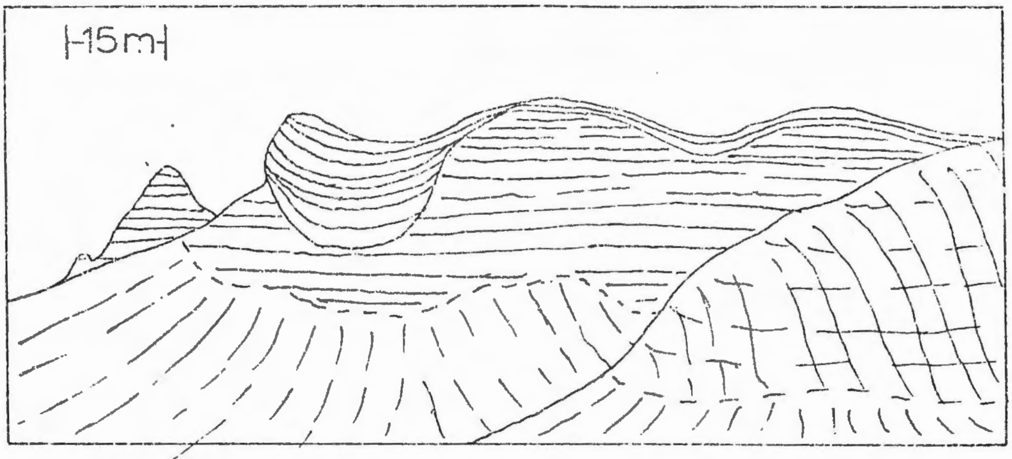


Fig. 9a. Sketch of channels cut into well-bedded tuff of the northern rim of Tuff Ring 2, Table Rock. Well-bedded sideromelane tuff fills the channels and drapes over the sides.

Fig. 9b. Photograph of a channel on the western rim of Tuff Ring 2, Table Rock; facing northeast. The channel is filled with well-bedded tuff from later eruptions.

slightly depressed by compaction in the center of the channel, bend upward and thin toward the channel walls. The uniformity of the bedding and lack of current structures suggest that deposition by air fall from later eruptions is more likely than reworking and deposition in the channels by running water.

Interbedded with the uppermost tuff beds and present within the fill of one channel on the east side of the ring are patches of white silicic tuff, which may be from any of several possible sources which occur within a 60 km radius of the tuff ring; these include the Newberry Caldera area, Cougar Mountain, and dozens of unnamed vents between the northern edge of the Fort Rock basin and Pine Mountain.

Within the crater and in some places extending for about 300 m beyond the crater edge, the tuffs have been altered to orange-brown, brittle, and massive palagonite without visible bedding. The contact between the massive palagonite tuff and the less altered sideromelane tuff above it is very uneven, crossing bedding planes. The restriction of intensely altered tuffs to the crater area may be due to hydrothermal activity which occurred late in the active phases of the volcano; there may have been enough steam generated to alter tuff beds in and near the vent, but not enough steam to explosively clear the vent.

Tuff Cone 3 (Table Rock)

Tuff cone 3 is located on the southern rim beds of tuff ring 2. It is a symmetrical cone about 1530 m in diameter at the base, tapering to a diameter of about 360 m, and stands 360 m high (fig. 10). The cone is capped with flat-lying basalt which once filled the crater, but erosion has modified the original cone, exposing the once-ponded basalt lava lake.

Most of the cone is composed of yellow-brown or orange sideromelane and palagonite lapilli-tuff beds in 1 mm to 2 m thick. Near the top of the cone, however, the tuff beds are gray-brown, and contain unaltered sideromelane. Overlying the uppermost tuff beds is a 1.5 to 6.5 m thick layer of massive black or red cinders and bombs which represents normal fire fountaining activity prior to the outpouring of fluid basalt which filled the crater.

The gray-brown tuff beds near the top of the cone may have been dehydrated by heat from the overlying lava lake (fig. 11). These are the only tuff beds in the Table Rock tuff cone which show no palagonitic alteration. Apparently the dehydration decreases the instability of the glass and prevents early alteration to palagonite.

The lava capping consists of vertically jointed aphanitic basalt. It is cut by four faults on its

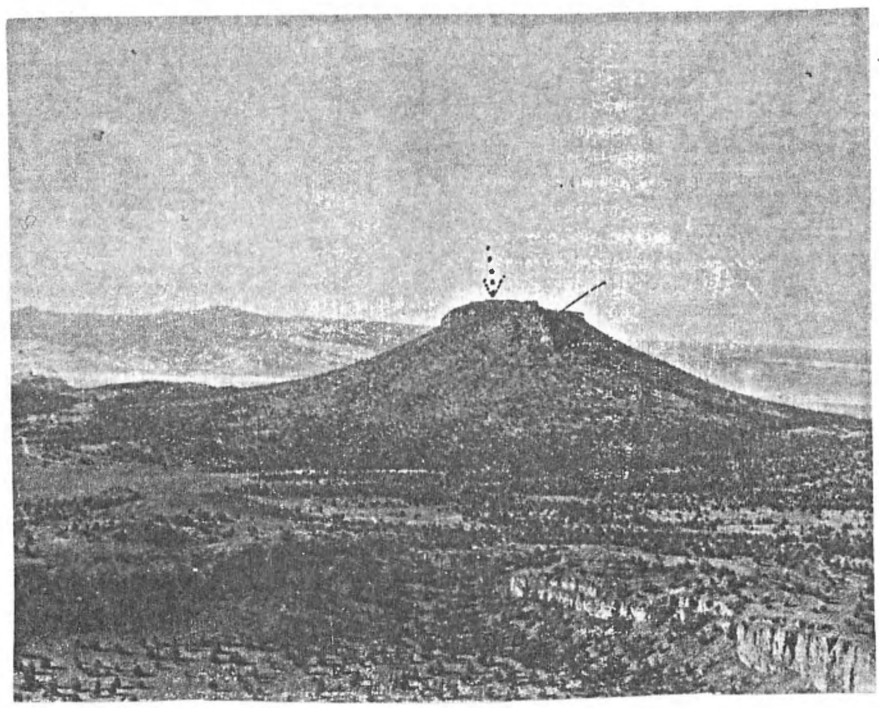


Fig. 10. Oblique aerial photograph of Table Rock (north side). The flat surface of the lava lake (dotted arrow) and large dike (solid arrow) are visible.

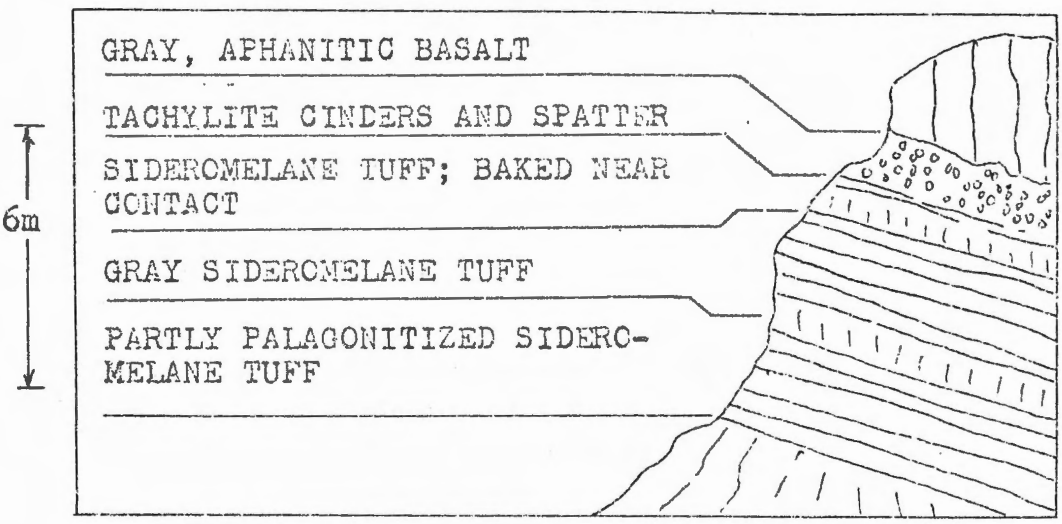


Fig. 11. Section of tuff exposed below the lava lake on the west and south side of the Table Rock tuff cone. A zone of tuffs (sideromelane) immediately below the former lava lake is not altered to palagonite. Tuffs elsewhere in the tuff cone are partly altered to palagonite, implying that dehydration of the tuffs immediately below the lava lake decreases the instability and resistance to weathering.

eastern side, (pl. 15 cross section C-C') with scarps which are 2 to 3 m high; each block is successively lower toward the eastern edge of the cap. Apparently faulting was caused by gravity sliding due to failure of less competent tuff under them long after volcanic activity ceased.

As suggested by the change from beds of hyaloclastic tuff to cindery ejecta followed by basaltic lava, water had access to the vent during most of the period of cone building. Late in the activity of the volcano, however, the source of water was cut off from the vent, which changed to normal cinder cone activity.

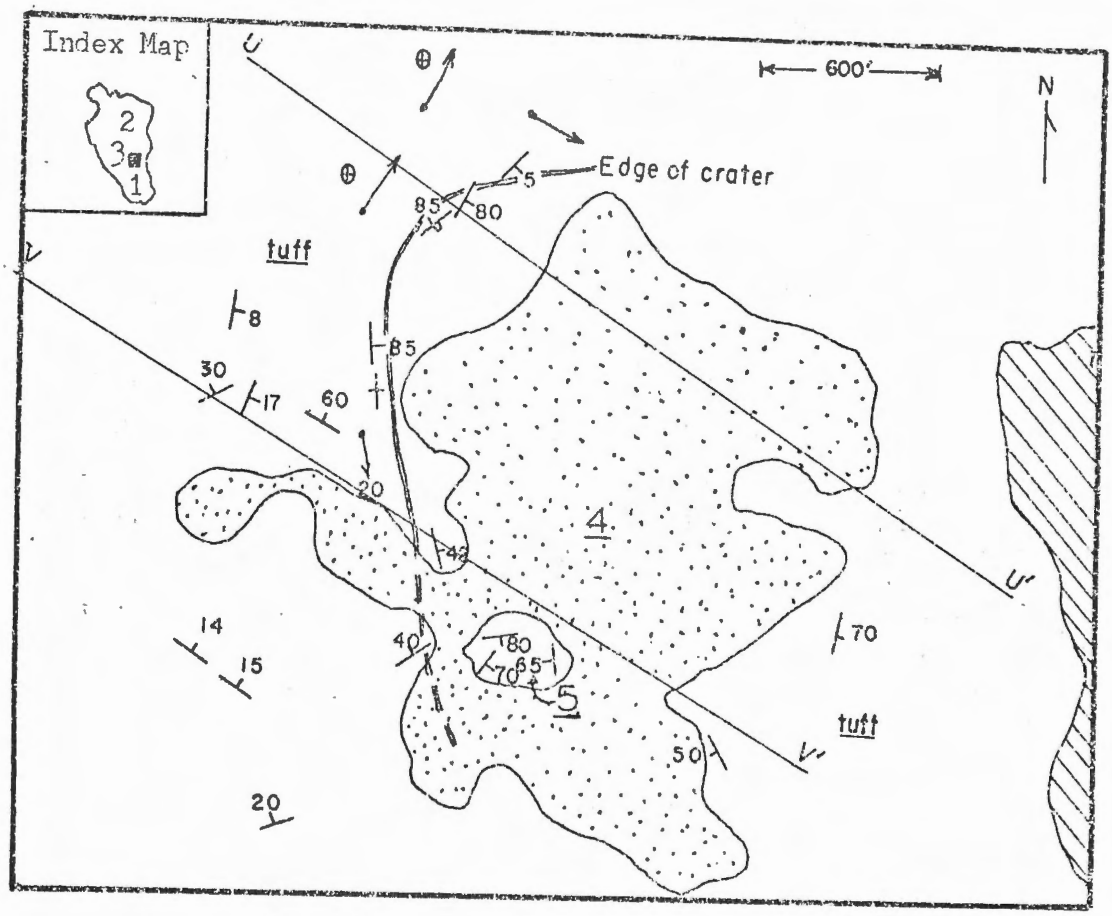
Vent 4

The area designated as vent 4 is a roughly circular depression about 360 meters in diameter. The depression is bounded on the west by steep slopes and cliffs, 46 m high, and on the east by low hills, and is drained by intermittent streams which flow east into Christmas Lake Valley.

The lowest rocks exposed around the crater edge of vent 4 are yellow-brown lapilli-tuff and tuff-breccia in beds about 1 m thick which contain from 10 to 40 per cent blocks of white and brown mudstone and vesicular basalt blocks. The uppermost beds, 1 mm to 0.5 m thick, consist of sideromelane tuff and lapilli-tuff.

Fig. 12-a. Sketch map of vent areas 4 and 5, Table Rock tuff ring complex. The map area is represented on the index map (inset) as a black square. An outline of the Table Rock tuff ring complex and the location of tuff rings 1, 2, and 3 are shown in the index map. The present crater edge of vent 4 is shown with a double line. Plain areas are bedded tuffs, stippled areas are crater lake sediments and alluvium, diagonal lines represent lake sediments of the Fort Rock - Christmas Lake Valley Basin. Vent 5 is located at the south edge of the crater of vent 4.

Fig. 12-b. Cross-sections U-U' and V-V'. The alternating stipple-line pattern represents bedded tuffs of tuff ring 2, the continuous line pattern represents bedded tuffs of vent 4, alternating line-dash patterns are crater lake sediments, and dotted patterns represent lake sediments underlying the tuff ring complex.


Index Map
2
3
1
U
V
600'
N
Edge of crater
tuff
4
5
tuff
U'
V'
85
80
5
8
85
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17
60
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42
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80
70
65
70
50
20

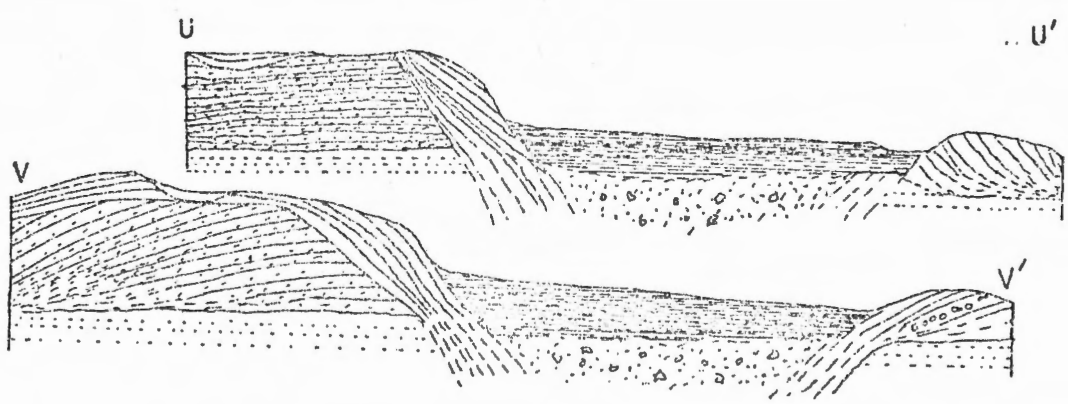
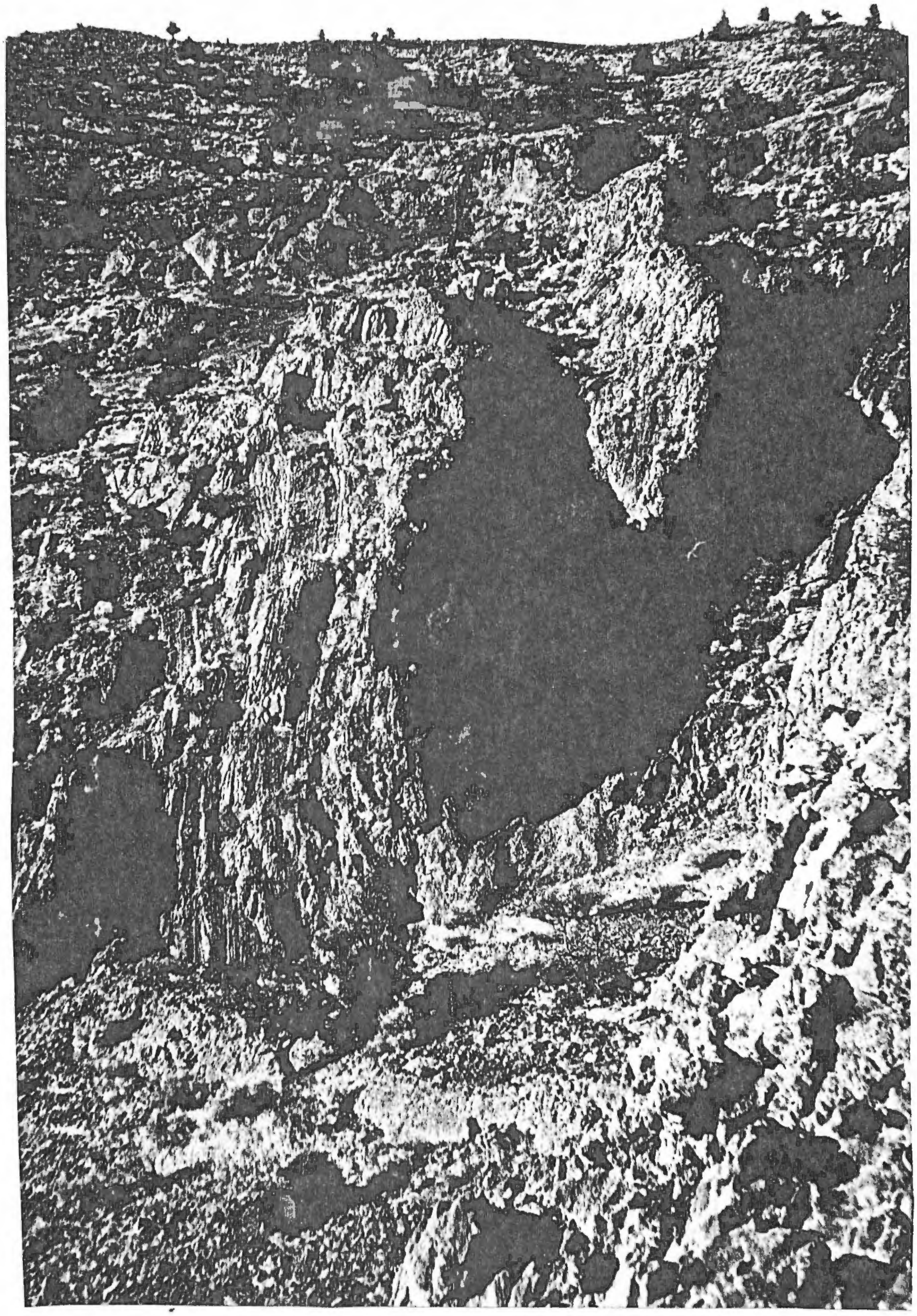

U
U'
V
V'

Fig. 13. West wall of the crater of vent 4, Table Rock tuff ring complex. The tuff beds dip into the crater with original dips of 40 to 85 degrees. The crater of vent 4 was excavated in tuffs of ring 2, and has near vertical walls. Thick sections of well-bedded tuff were plastered onto the crater walls during the late stages of the eruption of vent 4.



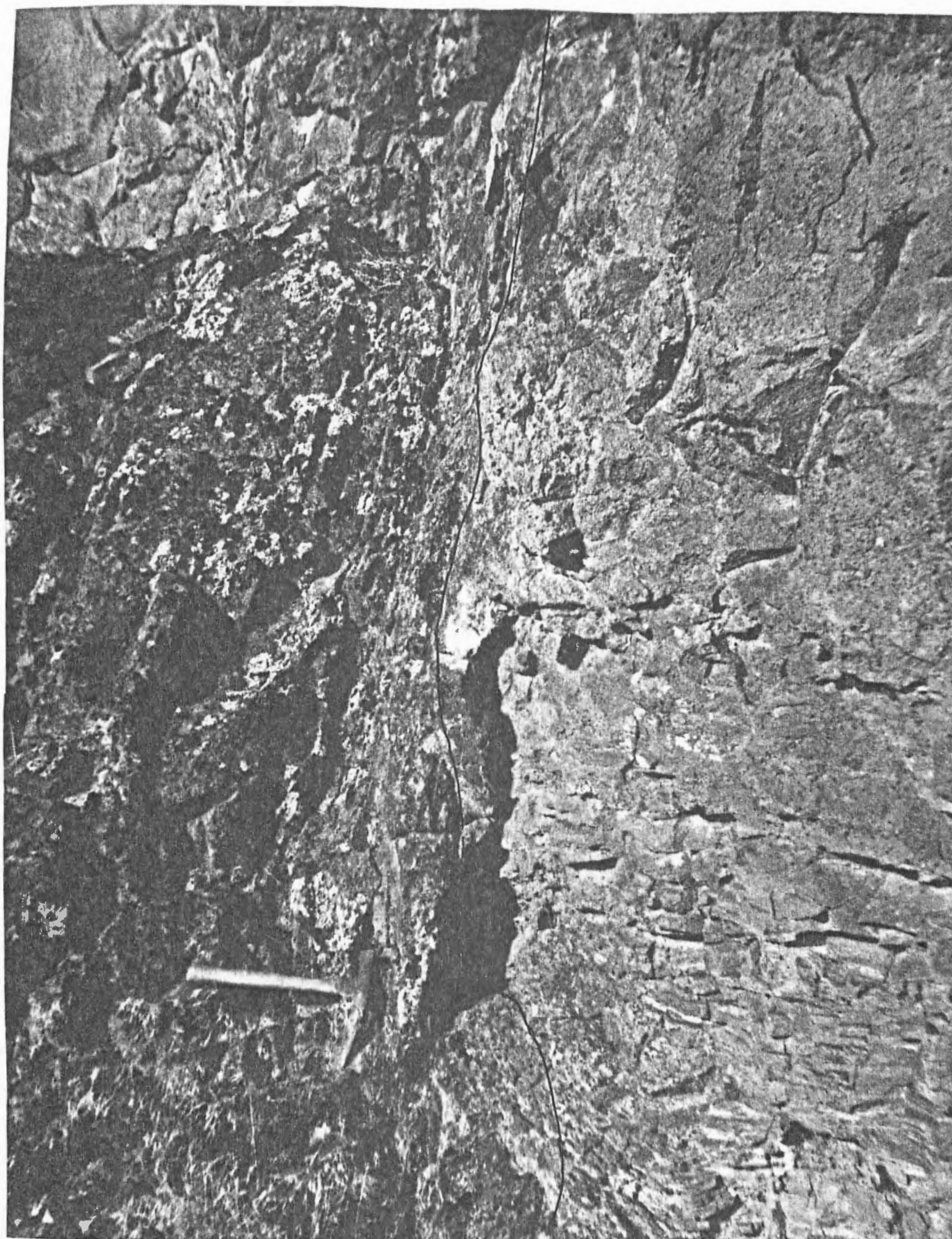


Fig. 14. The contact between nearly horizontal tuff beds of tuff ring 2 (right) and vertical tuff beds of vent 4, plastered onto the crater wall (the crater wall is outlined.)

Vent 4 was excavated in tuff which forms tuff rings 1 and 2, with walls sloping into the crater at angles of 30 to 85 degrees. Covering the walls and parallel to them are well-bedded, steeply dipping lapilli-tuff layers totaling 60 m thick (figs. 12, 13, 14). The lapilli-tuff beds are of uniform thickness along the length of the outcrop. They are steep within the vent, but outside they continue beyond the crater edge, and in conformance to the original surface, smoothly bend over and unconformably overlie tuff beds of tuff ring 2 (fig. 12). These relations show that the tuff was plastered against the crater walls during the eruption and remained in place with little slumping (fig. 13).

As shown by horizontal white mudstone beds of unknown thickness in the vicinity of the crater, a crater lake was formed after activity had ceased. The deposits lie nearly 30 m above the basin floor and were formed separately from the lake sediments of the adjacent Christmas Lake Valley.

Vent 5

Vent 5, on the southern edge of vent 4, is oval-shaped and is now represented by concentric tuff beds that originally filled the vent and have been exposed by erosion (fig. 15). Exposures occur within an outcrop about 18 m high, 45 m wide and 90 m long (fig. 16).

The beds, consisting of well bedded sideromelane lapilli-tuff and tuff, crop out around the outer edges of the vent where they dip inward at angles of 30 to 80 degrees (figs. 15,16). Steeper dips are most common near the base of the exposed conduit but become less steep near the original upper surface. The center of the conduit is filled with massive tuff-breccia containing blocks of lake sediment. Since blocks of lake sediments occur within the vent breccias and the tuff beds of vent 5 are in contact with a flat-lying white mudstone that overlies beds within the crater area of vent 4, vent 5 is clearly younger than vent 4. The tuff beds of vent 5 have a sharp contact with the lake sediments. Within 2 cm of the contact, the mudstone is brittle and cemented to the tuffs; it does not appear to have been sintered to the tuffs as a result of high temperatures.

The steeply dipping tuff beds which occur within the vent near its outer margin were deposited as cohesive ash that was plastered onto the walls during the latter stages of eruption. Continuing deposition progressively clogged the vent with ash, analogous to the grouting of pipes, as the activity waned.

Tuff Ring 6

Tuff ring 6, exposed in an outcrop located along the Silver Lake - Christmas Valley Road at the north end of the

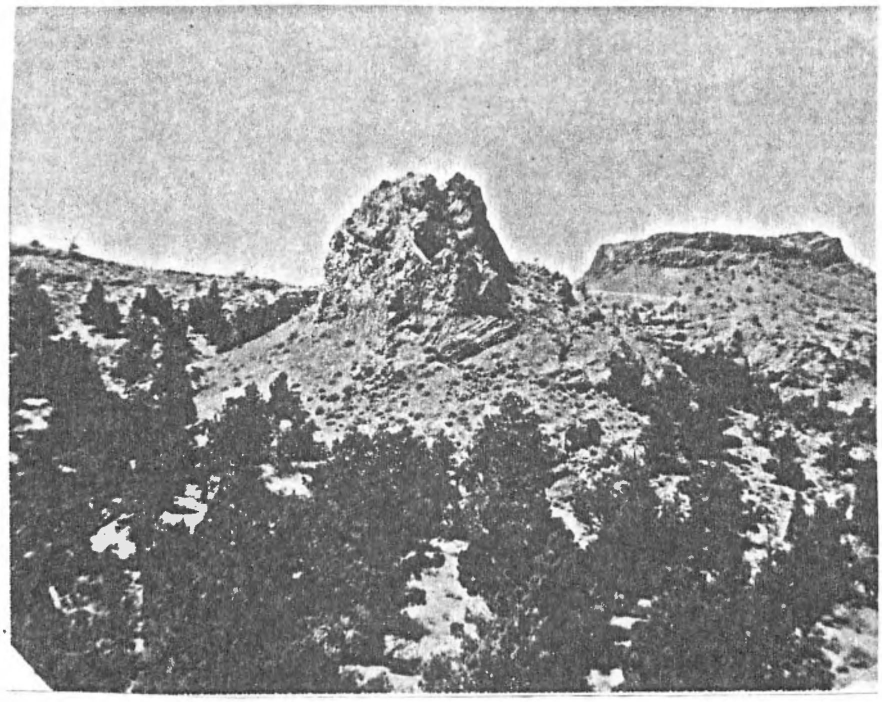


Fig. 15a. The southeast end of vent 5, Table Rock tuff ring complex. The flat topped peak in the background is Table Rock.

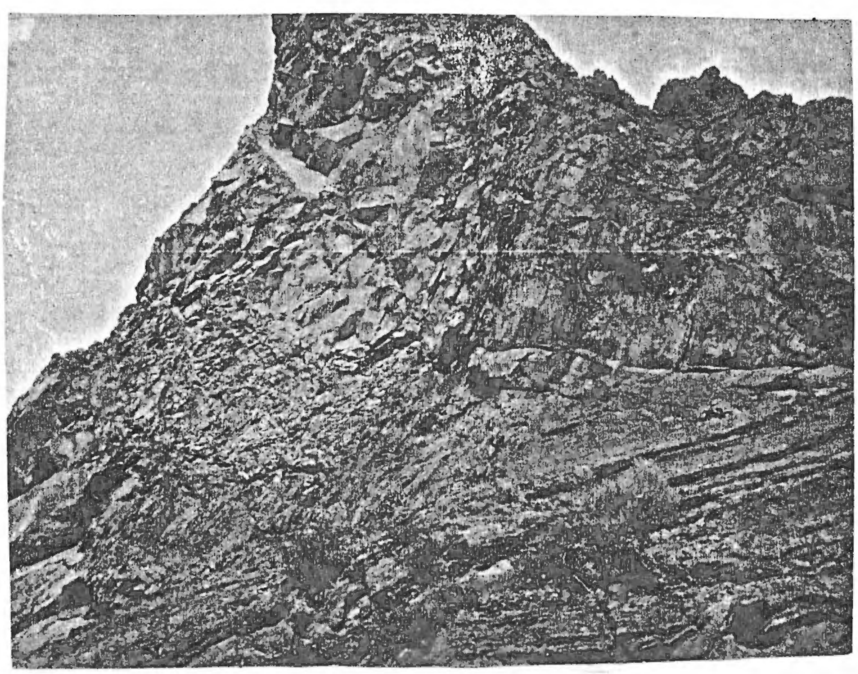


Fig. 15b. Close-up of the southeast side of vent 5, showing bedding dipping steeply into the conduit.

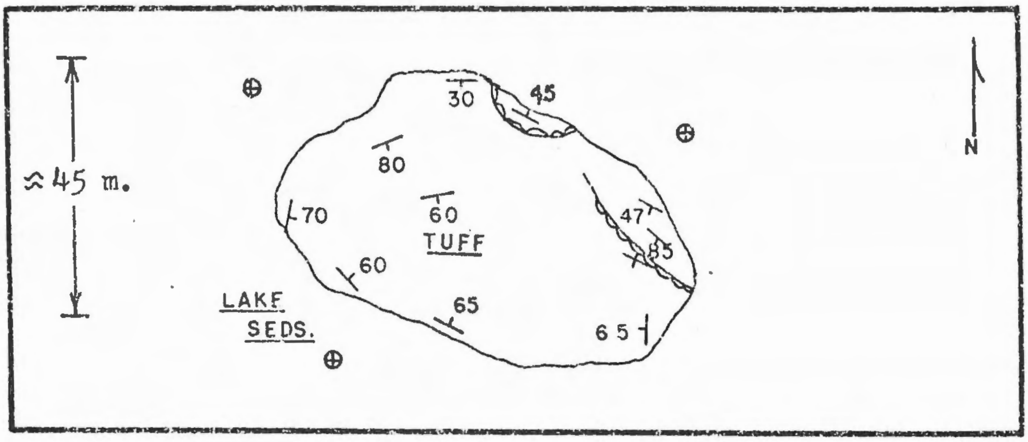


Fig. 16a. Sketch map of vent area 5, Table Rock tuff ring complex. Scalloped lines represent unconformities, with the scallops on the upper beds. The oval, concentric arrangement of the bedding shown by the arrangement of attitudes.

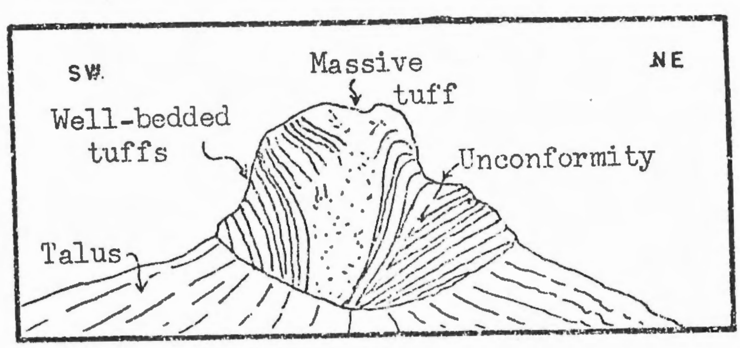


Fig. 16b. Field sketch of the southeastern end of vent area 5.

Table Rock tuff ring complex (pl. 1), is about 240 m in diameter and 25 to 30 m high. The outer slopes of the ring have been eroded away, leaving cliffs on all except the southwest edge where its deposits lap onto those of tuff ring 2. Typically, the deposits of tuff ring 6 consist of well bedded, yellow-brown sideromelane lapilli-tuff in beds of 1 cm to 60 cm thick. Angular basalt blocks make up about 5 per cent of the deposits near the center of the ring.

Tuff Ring 7

Tuff ring 7, located immediately east of tuff ring 6 at the northwestern edge of the tuff ring complex, is a nearly circular feature 480 m in diameter and 45 m high (fig. 17). Steep cliffs have been cut into the north and east sides of the ring by wave erosion. The crater, which was excavated in tuff along the rim of ring 2, is now drained by a small gully which runs north into the basin.

Well bedded, yellow-brown, partly palagonitized sideromelane lapilli-tuff occurs in beds 1 cm to a meter thick; they total about 46 m in thickness at the crest of the ring. Some beds contain small blocks of basalt and lapilli-size pieces of lake sediment. Ripple marks occur in well-bedded tuffs on the east edge of the ring; in association with bedding plane sags. Current directions and impact angles of blocks in the bedding plane sags confirm that the beds were derived from tuff ring 7.

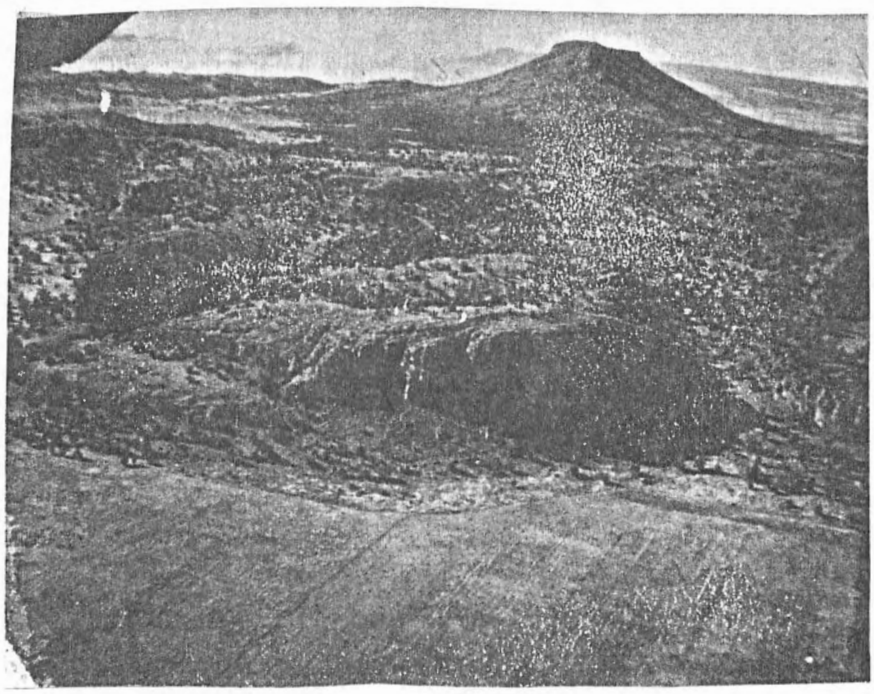


Fig. 17. Oblique aerial photograph of Tuff Ring 7 within the Table Rock tuff ring complex. The northern most exposure of the ring is outlined with a dotted line. The center of the ring and crater is below the arrow in the photograph.

Tuff within the center of the tuff ring is massive, poorly sorted, and contains 3 to 4 per cent angular to subangular basalt blocks.

Vent 8

A small vent and tuff ring remnant are exposed in cross-section along the cliff at the north end of tuff ring 2. The vent is about 27 m wide and the tuff ring has a radius of 120 m. The vent has vertical walls which transect tuff beds of ring 2 in sharp contact. Well-bedded yellow-brown sideromalene lapilli-tuff layers 3 cm to 2 m thick within the vent are vertical and lie parallel to its walls, except near the center where some of the beds appear to have slumped (fig. 18).

The layers can be traced onto the upper surface of ring 2 on the northeast side. The lower 6 m of ejecta is massive lapilli tuff which is beneath well-bedded lapilli-tuff up to 9 m in thickness.

As with vent 5, vent 8 is nearly concentric and is filled with vertical layers which are parallel to the vent walls. It appears that sticky ash plastered the walls of the vent and eventually clogged it in the last stages of the eruption, but unlike vent 5, there is no central zone of massive tuff-breccia.

Vent 9

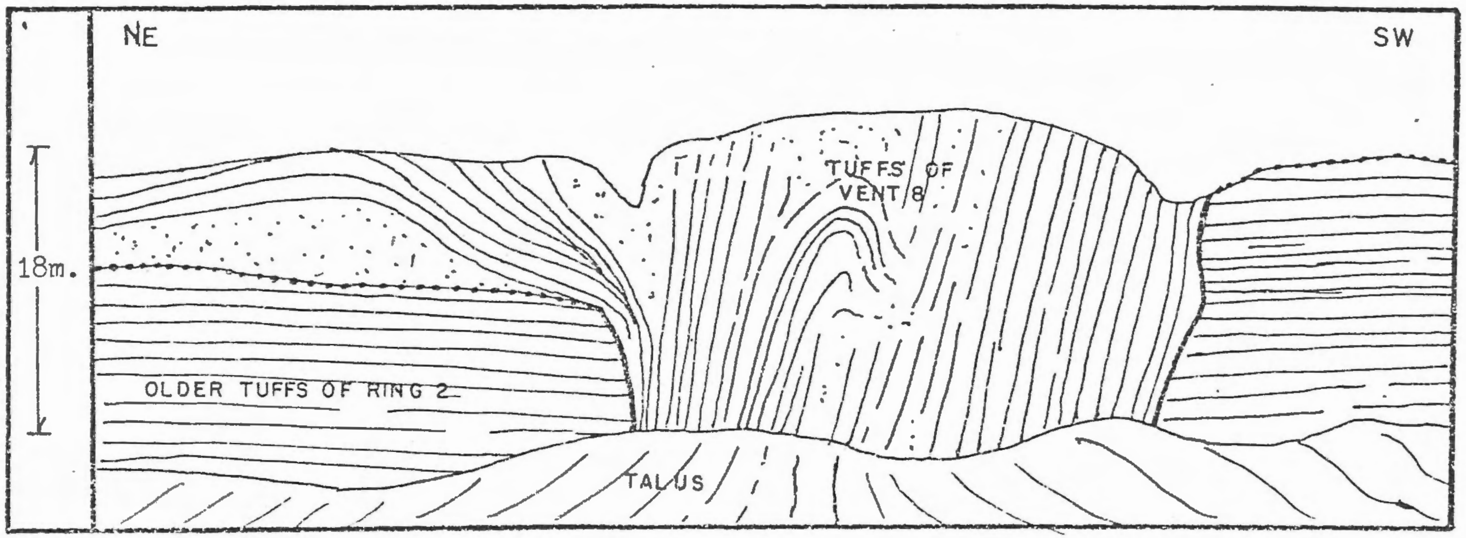


Fig. 18. Sketch of the cliff face in which vent 8, Table Rock tuff ring complex, is exposed. Heavy dots outline the ground surface prior to the eruption of vent 8. A remnant of a small tuff ring around the vent is visible on the left side of the vent.

Vent area 9, located at the southeastern end of Tuff Ring 1, crops out as a knoll which is 6 to 9 m high and has a diameter of about 30 m. The contact between the vent and the rocks through which it cuts, however, is not exposed. Rocks exposed around the outer edge of the vent are well-bedded tuff beds, 1 cm to 75 cm thick, and are arranged in a concentric pattern with nearly vertical dips. On the east side, the beds appear to be overturned but were apparently plastered onto an overhanging wall (fig. 19). The central portion of the vent contains massive palagonite tuff. About 30 m west of the rocks exposed in the knoll are well bedded tuff beds dipping gently toward the vent. These are probably part of the tuff ring around vent 9.

The concentric, near-vertical beds are similar in pattern to those in vents 5 and 8. All three of the small vents described here appear to have been filled by the continued plastering of sticky tuff onto conduit walls. Apparently rapid filling of the vents prevented slumping and enabled the beds to be preserved in a vertical position.

FORT ROCK

Fort Rock with its spectacular wave-cut cliffs (fig. 27), is the best known tuff ring in the area. It has been described in part by Peterson and Groh (1963),

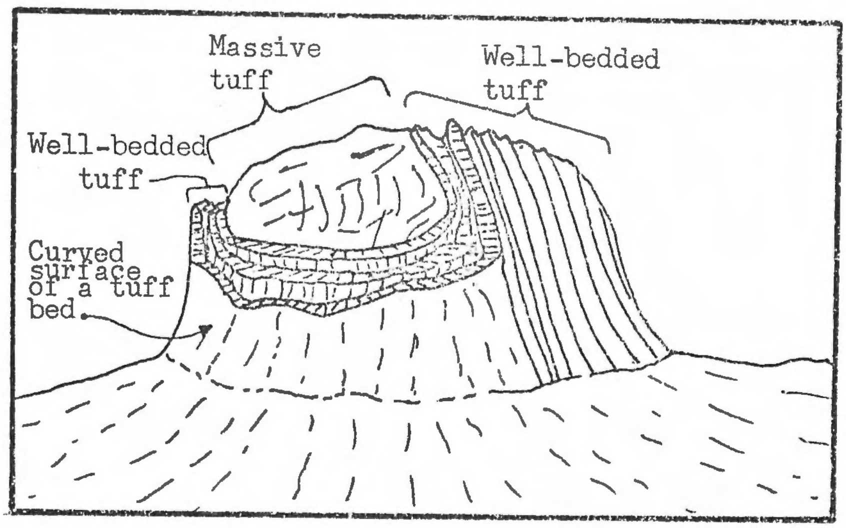


Fig. 19a. Sketch of vent 9, Table Rock tuff ring complex, showing the concentric arrangement of tuff beds around the outer edges and massive tuff in the center.

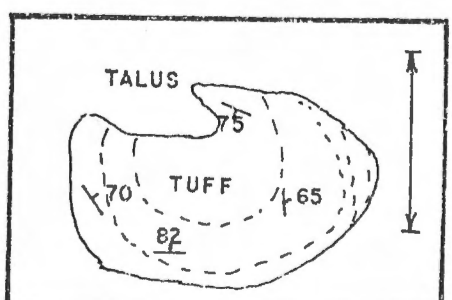


Fig. 19b. Sketch map of vent 9. Dotted lines represent the geometry of beds which are actually less than a centimeter to several meters thick. The scale on the right is 30 meters long.

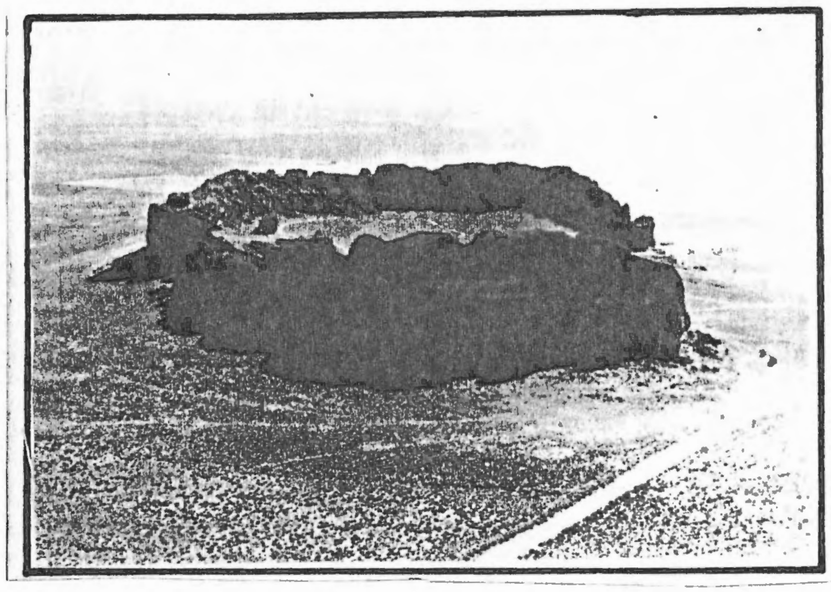
Hampton (1964), Allison (1966) and Waters (1967). (See plate 5).

The ring is 1360 meters in diameter and 60 meters high at its crest. The present crater floor is 6 to 12 meters above the floor of the lake basin. The south side has been breached by waves of a former lake, giving easy access to the crater. There is a lake terrace cut into the ring at an elevation of 1349 meters, 20 meters above the floor of Fort Rock Valley.

The ring is composed of orange-brown lapilli-tuff in beds of one cm to one m thick. Beds can be traced for up to 60 meters from the inside to the outside of the ring without any change in thickness. Graded beds are common. Some of the lapilli at the base of graded beds are accretionary, consisting of a one or two cm glass fragment with a coat of fine glass particles.

The original shape of the crater can be inferred, if the inward-dipping beds are parallel to the crater wall. It is funnel shaped, with the innermost beds dipping inward at angles of 20 to 70 degrees.

A distinct angular unconformity within the inward-dipping layers above it is present on the west side of the ring (fig. 20). Along the east side at the same position within the ring, however, are inward-dipping fractures, along which the inner block of tuff beds have



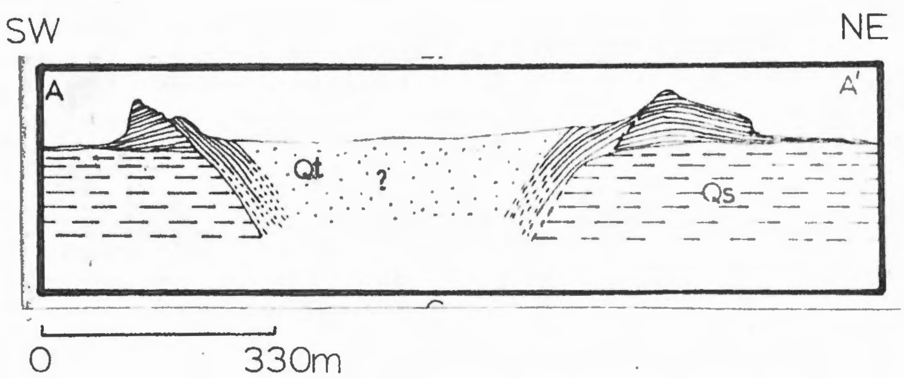


Fig. 20. Photograph and cross-section of Fort Rock. Flat, dashed lines represent lake sediments. Solid lines (dashed where inferred) represent the bedded tuffs of the ring.

slumped. The unconformity, as well as the fracture planes, dip into the crater at 40 degrees, and appear to have formed as the result of slumping into the former crater. Continued eruptions deposited well-bedded ash, possibly reworked from materials within the slump block, on the scarp.

HOLE-IN-THE-GROUND

Hole-in-the-Ground is located several miles beyond the northwestern edge of Fort Rock Valley. The crater is not dissected by erosion, and is partially covered by recent Mazama Ash (fig. 21).

The best description of the crater and ring is by Waters (1967)

> "Hole-in-the-Ground is a circular pit, 5000 feet in diameter and 425 feet deep. The original pit was much deeper; it has been partly filled by lake deposits, ash falls and debris which has fallen or been washed down the steep inner slopes of the crater. A thin blanket of ejecta, in most places less than 100 feet thick, drapes over the crater rim and thins outward to an indefinite edge in about one mile. Clustered along the rim as part of this ejecta, are great blocks of rock 3 to 10 feet in diameter. Some of these have been rifted from the two basalt flows exposed in the walls of the crater. Other huge blocks are composed of a distinctive highly porphyritic basalt and of rhyolite and a variety of ignimbrite not found in the crater walls; they obviously have been blown up from far below the present floor of the crater. Mixed with this coarse debris in the ejecta blanket is a matrix of various sized volcanic particles ranging downward

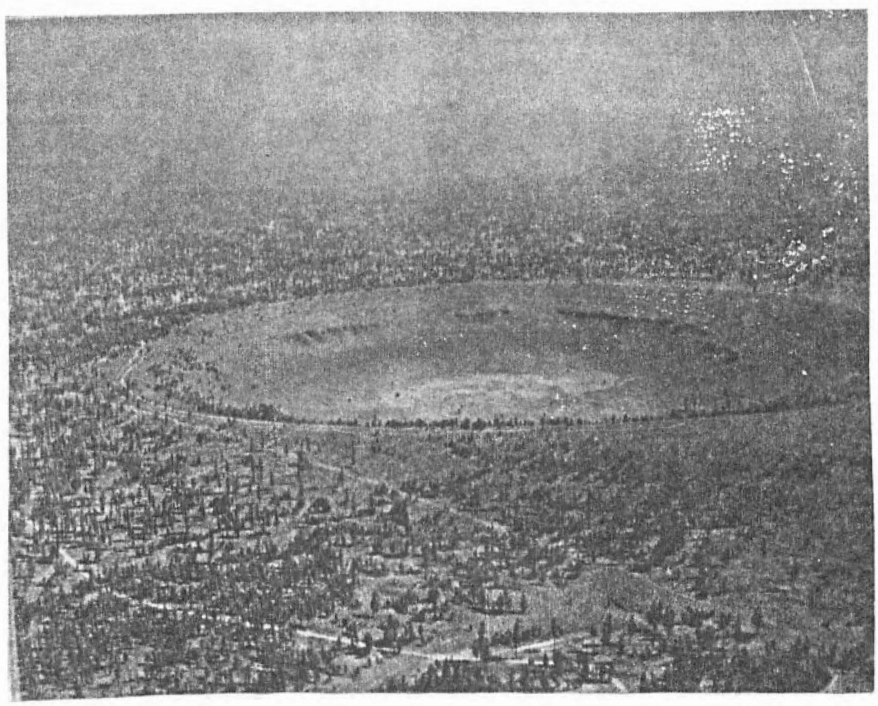


Fig. 21. Oblique aerial photograph of Hole-in-the-Ground, facing north. Photo 65-3, Oregon State Department of Geology and Mineral Industries.

> to fine silt. A crude stratification in the ejecta demonstrates that the ejecta blanket was not formed in one grand explosive event, but is the product of intermittent jets of steam bursting out of the Hole over a period of time."

The ejecta ring differs from rings elsewhere in the basin, in that none of the beds dip into the crater area. The crater walls are fairly well-exposed and are not covered by inward-dipping, bedded lapilli-tuff.

BIG HOLE

Big Hole is a circular crater 1820 meters in diameter and 130 meters deep, located along Oregon Highway 31, 18 miles (29 km) southeast of La Pine (fig. 2). It is surrounded by an ejecta ring 24 to 30 meters thick at the crest and extending 1800 to 2500 meters beyond the crater edge. The ring is highest on the northeast side of the crater at Big Hole Butte. There is a poorly exposed, small parasitic vent on the north side of Big Hole Butte.

The ring is composed of moderate to well-bedded lapilli-tuff and tuff-breccia, in beds 5 cm to a meter thick. Tuff-breccia beds include porphyritic basalt blocks up to 2.5 m in diameter within a matrix of sideromelane lapilli-tuff. The tuff beds are deformed by abundant bedding plane sags.

Convolute bedding, involving a 6.1 m thick section of tuff beds, is exposed near the eastern crest of the

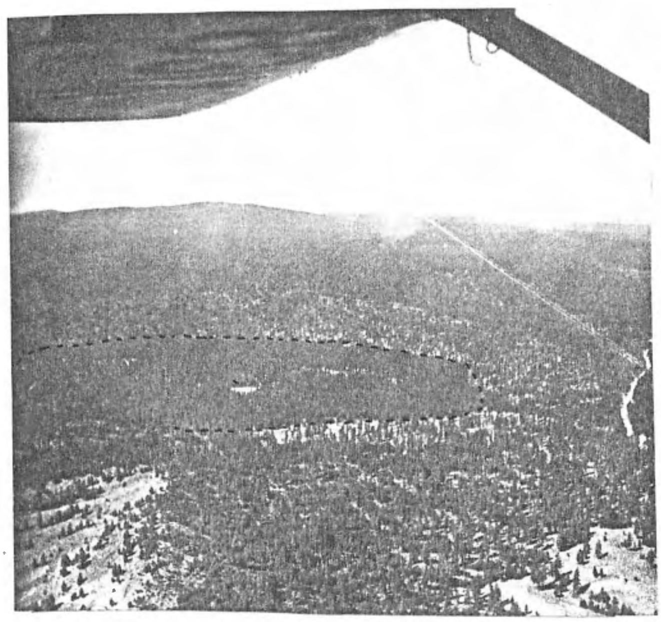


Fig. 22. Oblique aerial photograph of Big Hole, facing southwest. The edge of the crater floor is outlined with dashes.

tuff ring. The lateral extent of exposed folded beds is about 45 m (fig. 43). Bedding was deformed into asymmetrical folds by detachment and sliding down slopes of 2 to 5 degrees. It is possible that slumping was triggered by seismic activity associated with the eruption.

The ejecta rim of Big Hole is thicker on the northeast side of the ring. This asymmetry appears to be due to prevailing winds at the time of eruption. Moffitt Butte and Hole-in-the-Ground are also asymmetrical, with thicker sections of tuff beds on the northeast side. The prevailing wind is from the west at present and may have been so throughout Pleistocene time.

Inside the south crater wall a flat terrace or ledge, up to 152 m wide, lies 50 m below the crater rim. It appears to be the top of a large block of the rock underlying the ejecta rim which has slid into the crater. Subsidence of such a block would account for the large crater volume and relatively small amount of country rock fragments in the ejecta.

MOFFITT BUTTE

Moffitt Butte is a heavily gullied tuff ring, 1400 m in diameter and 120 m high at the crest. It is located 16 km south of La Pine adjacent to Oregon State Highway 31 (fig. 2). The flat crater floor is about 80 m above the surrounding plain. A small parasite vent and ring, 510 m in diameter, is located on the southwestern flank of the larger ring.

The ring consists of sideromelane lapilli-tuff in graded and ungraded beds 3 cm to 30 cm thick, but the average bedding thickness decreases from 15 cm near the base to 5 cm near the crest of the ring. The tuff beds contain from two to five per cent angular basalt blocks. Small scale convolute bedding is present in some parts of the tuff ring.

An unconformity near the crest of the ring dips inward toward the crater at an angle of 20 degrees and truncates beds which dip outward at an angle of 35 degrees. The unconformity is overlain in places by a 1 m thick bed of angular basalt blocks which average about 30 cm in diameter. The block bed is overlain by 18 m of very well-bedded lapilli-tuff, dipping into the crater parallel to the unconformity (cross-section A-A', pl. 3).

The crater of the parasite vent was filled with lava issuing from a vertical dike on its northwest edge. The crater lake consists of vertically-jointed, gray, aphanitic basalts in an exposure 11 m thick. As with the bedded sideromelane tuff beds which lie immediately below the lava lake at Table Rock, the tuff is unaltered (fig. 23).

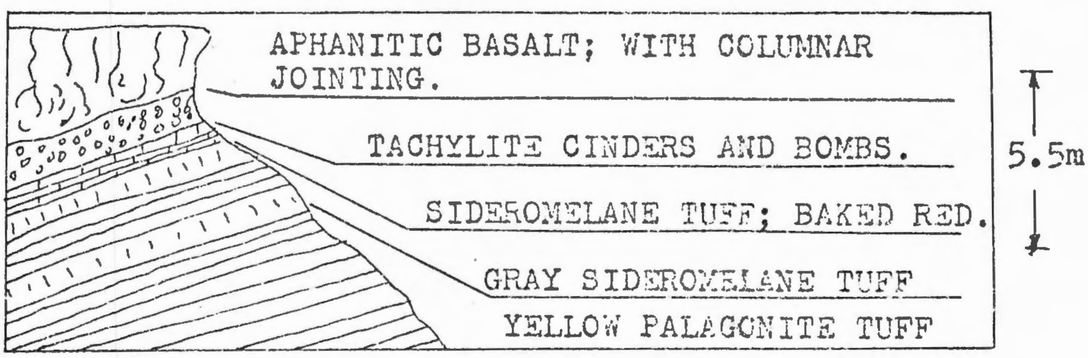


Fig. 23. Section of tuffs exposed immediately below the lava lake in the parasitic vent on the south side of Moffitt Butte. Bedded sideromelane tuff close to the overlying lava lake is not altered to palagonite.

TABLE MOUNTAIN

Table Mountain is located at the northwest edge of the Fort Rock Basin. It is composed of 2 overlapping tuff rings, 1.6 km by 3.2 km in plan view and is oriented NNE-SSW. The northern ring of Table Mountain is a flat topped ridge 76 m high and 460 m long. The southern ring has a flat basalt cap 150 m in diameter. Exposures of tuff, however, are very poor.

The tuff rings are composed mostly of well-bedded sideromelane tuff and lapilli-tuff in beds which range in thickness from 0.5 cm to a meter. The lapilli-tuff layers commonly contain about 1 to 2 per cent angular basalt blocks although in the southern ring beds contain from 2 to 5 per cent well rounded obsidian pebbles and sand derived from a beach deposit underlying the tuff ring.

Cropping out on the eroded flanks of the rings are 7 dikes and a sill, with widths of 1 m to 9 m (plate 4). The sill dips in toward the crater, parallel to inward-dipping tuff beds.

Both the northern and southern craters contained lava lakes, now exposed at their eroded edges. Lava spilled over the north edge of the northern ring and down the outer slope. Lava flows between the two rings and on the south flank of the southern tuff ring were fed by dikes which broke through the flanks.

TUFF RING LOCATED 5 Km SOUTH OF TABLE MOUNTAIN

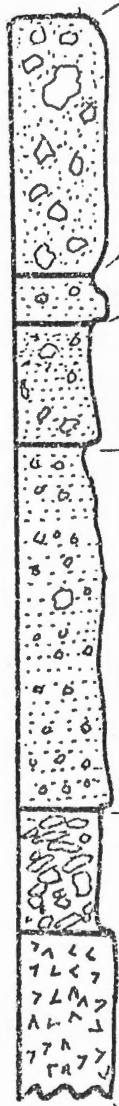
The remnants of this ring, 1.7 km in diameter, are barely visible on the flat valley floor because wave action has leveled it to a low-lying flat mesa, with its surface 6 to 9 m above the surrounding plain.

The tuff ring consists of moderately well bedded palagonite tuff, lapilli-tuff, and tuff-breccia in beds 3 cm to a meter in thickness. Some of the tuff-breccia beds contain 10 to 40 percent angular to rounded basalt blocks. None of the tuff-breccia beds are graded. Attitudes measured in the bedded tuff outline a circular, anticline-like structure typical of a tuff ring.

Gravel bars, consisting of well-rounded pebbles and cobbles of palagonite tuff from the ring, extend northeast of the ring and were derived from it.

HORNING BEND

Horning Bend is a tuff ring which overlies a dome of cryptocrystalline dacite, located at the northern end of the Connely Hills (fig. 2). The dome is cut by a 30 m wide vent, now filled with basalt, at its northern edge. Sideromelane tuff-breccia and lapilli-tuff erupted from this vent partly buried the dome and filled much of a canyon which had been cut into the dome prior to the eruption. Bedded tuffs also overlie lake sediments for 960 m north of the base of the dome.



THICKNESS (METERS)	DESCRIPTION
2	Massive tuff-breccia consisting of about 25% blocks of light gray dacite and scoriaceous basalt in a matrix of sideromelane tuff and lapilli-tuff.
.3	Graded lapilli-tuff.
1	Well-bedded, tan to cream-colored tuff and lapilli-tuff. There are about 10% blocks of dacite. Excellent bedding plane sags present.
3	Well-bedded lapilli-tuff; some showing poorly defined grading. Most of the lapilli-size material is dacite from the underlying dome. The beds are 2 cm to 1 m thick.
1	Very poorly sorted talus which covered the sides of the dome prior to burial with sideromelane tuffs. Most of the talus consists of dacite blocks in a matrix of brown sandy silt.
	Dacite dome.

Fig. 24. Measured section of sideromelane tuff, lapilli-tuff, and tuff-breccia which overlies the dacite dome at Horning Bend.

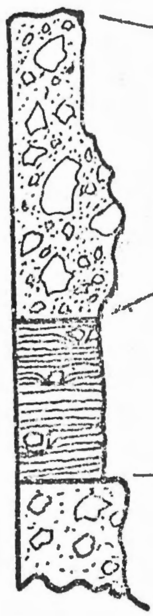
Well-bedded tuff-breccia and lapilli-tuff in beds 1 cm to 2 m thick and totaling 9 m in thickness, have primary dips ranging from 10 to 40 degrees paralleling the slope of the underlying pre-tuff topography. The tuff-breccias contain about 25 per cent blocks of angular, light gray dacite derived from the dome and scoriaceous basalt which rest in a matrix of sideromelane tuff. The blocks are angular and range in diameter from 15 cm to a meter. Well-bedded lapilli-tuff beds display abundant bedding plane sags and current structures. Low angle cross-bedding indicates current directions moving away from the vent area (fig. 25).

TUFF RING NEAR BOATWRIGHT RANCH

Boatwright Ranch is located 7.2 kilometers south of the town of Fort Rock, at the southern edge of Fort Rock Valley. The tuff ring is a low, juniper-covered hill 1.5 kilometers west of the ranch house. The poorly exposed ring is 1.7 kilometers wide, about 30 meters high at the south end and 15 meters high at the north end. The north and west side are partly buried by later basalt flows.

The ring is composed of very well-bedded sideromelane lapilli-tuff and tuff-breccia in layers from 1 cm to 15 cm thick. Graded bedding is common. Bedding plane sags formed by impact of blocks into the well-bedded lapilli-tuff are abundant (fig. 27).

Fig. 25. (Opposite page) Bedded lapilli-tuff and tuff-breccia, Horning Bend tuff ring. Cross-bedding in the center of the photo may be due to base surge clouds moving away from the vent. Impacting blocks thrown from the vent formed the bedding plane sags (blocks are outlines).



THICKNESS (METERS)	DESCRIPTION
4.6	Massive tuff-breccia. Angular blocks of basalt and dacite, up to 8 feet in diameter, in a matrix of light brown sideromelane tuff.
2.4	Very well-bedded lapilli-tuff with graded beds and abundant bedding plane sags (block sags). Lapilli-size pumice at the base of each graded bed is partially altered to palagonite.
0.7+	Massive tuff-breccia. Blocks of black, aphanitic basalt and light-gray dacite in a matrix of sideromelane tuff.
	Talus covers base of section.

Fig. 26. Measured section of sideromelane lapilli-tuff and tuff-breccia exposed along the northeast edge of the tuff ring near Boatwright Ranch.

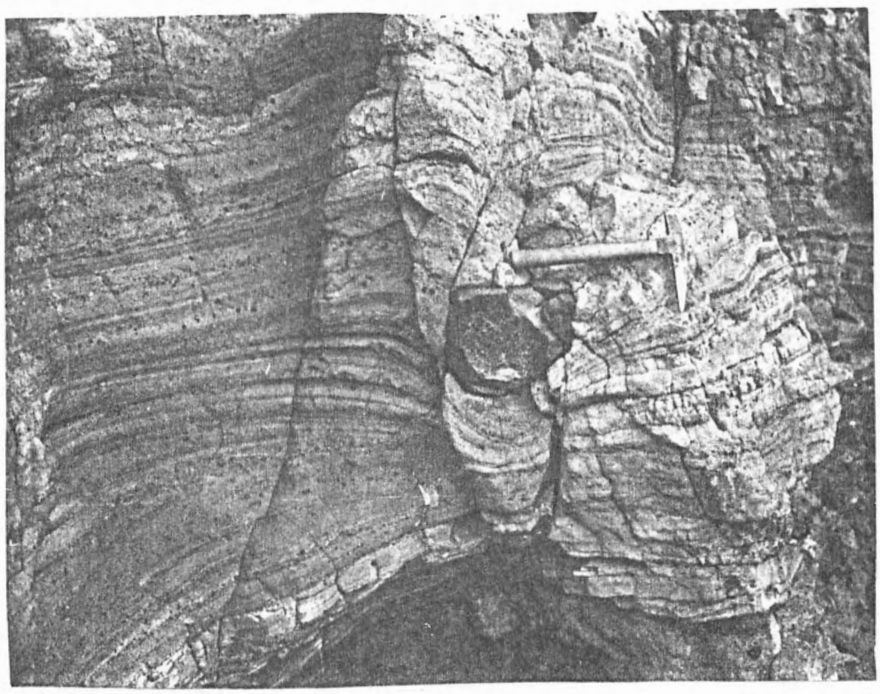


Fig. 27. Well-bedded tuff and lapilli-tuff in the tuff-ring at Boatwright Ranch. Photo taken along the north-eastern rim of the ring. Excellent examples of graded bedding are visible, graded from lapilli to fine tuff size. The bedding plane sag in the center was formed by the impact of the block visible below the hammer handle.

The breccias are composed of 1 cm to 2 meter diameter blocks (dark gray basalt and light gray dacite) which lie in a matrix of sideromelane tuff.

Wave action has eroded a terrace around the eastern flank of the ring. The shape of the ring has been modified by erosion to the extent that structural data was needed to locate the position of the vent.

TUFF RING ON THE SOUTHWEST EDGE OF GREEN MOUNTAIN

Two tuff rings are located on the southern slope of Green Mountain, a low, basaltic shield volcano on the northern edge of Christmas Lake Valley. The tuff ring on the southwest slope is about 700 meters in diameter and 46 meters high. Outer slopes are 20 to 30 degrees, parallel to bedding. The original extent of the ring is indicated by a shallow depression 240 to 900 meters wide. The depression was formed by thin lava flows which flowed around the ring, followed by erosion of the less resistant tuff of the outermost slopes.

The ring is constructed of very well-bedded sideromelane lapilli-tuff in beds 2 cm to 15 cm thick. Less than 0.1 per cent of the ejecta is composed of basalt blocks. Maximum thickness of the tuffs is 46 meters at the crest, thinning to zero at the edges. Graded bedding is common, with lapilli-size sideromelane fragments or accretionary lapilli at the base of each bed, grading up into fine tuff-size fragments. In some graded beds the lapilli at the base form an open network, with no fine-grained matrix. Current cross-bedding with an amplitude of about 2 centimeters is present only in beds on the east flank. The only bedding plane sags occur in coarse, lapilli-size material where deformation is not pronounced.

The ring is a circular, anticline-like structure, truncated on the inside by an unconformity which dips into the crater at angles of 30 to 40 degrees. This surface is covered by bedded tuffs which have been altered to palagonite. Some of the bedding in the outer flanks of the ring has a wavy appearance, due to draping of tuff over irregularities in the pre-existing topography.

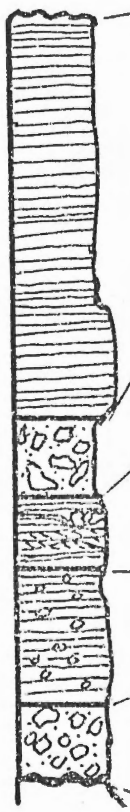
The crater is partly filled with the remnants of a lava lake; where it is exposed along the crater edge, the basalt flows in the lake are 4.5 m thick.

A dike cuts the northwest side of the tuff ring. At its widest point, where it measures 6.2 meters, it is covered with twisted, ropy lava and spatter which forms a small spatter rampart. The dike narrows to 15 cm at the crest of the ring, near the edge of the outcrops of the lava lake.

TUFF RING ON THE SOUTHERN SLOPE OF GREEN MOUNTAIN

This tuff ring is located at the western edge of a sequence of recent basalt flows which cover the southeastern part of Green Mountain. The main exposures are of the southeastern part of the ring, in a 26 m high bluff which is 630 m long. Outcrops of lapilli-tuff, including the bluff, occur within a crescent-shaped area which is 600 m wide and 1050 m long. The western and central portions of the ring have been eroded and covered by lava flows from vents higher on Green Mountain.

Most of the exposed part of the tuff ring consists of very well-bedded sideromelane lapilli-tuff which contains less than one per cent angular basalt blocks. Graded beds, with accretionary lapilli at the base, are common. Some of the finer grained beds of tuff and lapilli-tuff are deformed by bedding plane sags and convolute-type bedding. Small-scale dunes, with an amplitude of about 2 cm, show current directions which are radial about the crater area. Interbedded within the tuff sequence are several 2.1 to 2.4 m thick beds of tuff breccia. The representative measured section (fig. 28) shows a general decrease in the average grain size of ejecta from the base to the top. The upper 12 m of section, for example, contains no blocks or bombs. During the early, crater-forming phases of the eruption, however, abundant blocks were deposited along



THICKNESS (METERS)	DESCRIPTION
12.2	Two to 10 cm thick beds of graded lapilli-tuff. Bedding traced along strike shows no appreciable change in the thickness. No blocks or bombs present.
2.4	Tuff-breccia; 50 to 60 per cent angular blocks of dark-gray, aphanitic basalt in a matrix of sideromelane tuff.
2.1	Very well-bedded tuff and lapilli-tuff. Present is graded and reverse-graded bedding, cross-bedding and bedding plane sags.
4.3	Moderately well-bedded lapilli-tuff with a few basalt blocks.
2.0+	Tuff-breccia, consisting of randomly oriented, angular basalt blocks in a matrix of light brown sideromelane tuff.
	The base of the section is covered with talus.

Fig. 28. Measured section of tuff, lapilli-tuff, and tuff-breccia along the east side of the tuff ring on the southern slope of Green Mountain.

with juvenile ejecta. Later, after an equilibrium crater shape had been reached (i.e., when material was vented without further erosion of crater walls), only juvenile ejecta was deposited.

On the west, or inner side of the tuff ring, the tuff beds are truncated by a sharp unconformity, dipping inward at an angle of 52 degrees. The unconformity surface is covered by a meter thick layer of massive lapilli-tuff. From attitudes of the tuff beds, orientation of current structures and bedding plane sags, and the shape of the unconformity, the approximate vent area was located (pl. 9).

SEVEN-MILE RIDGE

Seven-Mile Ridge is a group of five overlapping tuff rings, aligned along a northwest-southeast trending fault on the southern edge of the Christmas Lake Valley Basin (fig. 2). The complex is 12 km long and 3.2 to 4.8 km wide.

The three best-preserved rings within the complex are located at the southern edge of Seven-Mile Ridge at or above former lake level (fig. 29) and lie on top of a tilted block composed of lava flows. Tuff beds from the largest of the three rings partly buried the fault scarp, which has a maximum height of 61 m. The two northernmost tuff rings have been eroded by waves to flat-topped mesas, 9 to 18 m high.

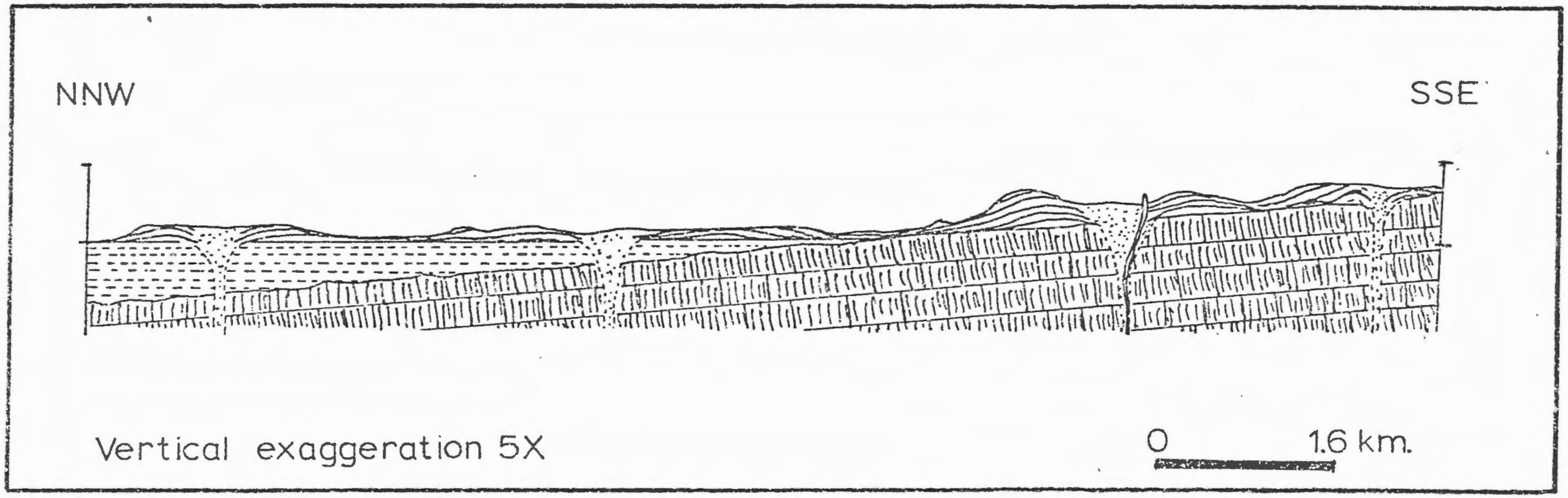


Fig. 29. Sketch cross-section along the axis of Seven-Mile Ridge. Tuff, lapilli-tuff, and tuff-breccia are represented by closely spaced solid lines, lake sediment by dashed lines and plateau basalt flows by irregular, vertical lines.

The contact between tuffs of the three southern rings and underlying clastic sediments or talus is very irregular. Old creek channels which drained into the lake and later filled with the tuff and tuff-breccia from the tuff rings are now being resurrected. This is well-displayed along the western edge of Seven-Mile Ridge where modern streams have cut into the ancient breccia-filled gullies (fig. 30-b).

The lowest beds within the tuff ring complex are best exposed in the 3 northern tuff rings. They consist of beds of tuff-breccia, 0.5 to 9 m thick, which contain 10 to 50 per cent diatomite blocks and angular basalt blocks and bombs set in a matrix of dark orange-brown sideromelane tuff (fig. 31-a). Blocks of diatomite, which occur within the breccia near the vents, indicate that the eruptions occurred within or near the edge of the ancient lake. The diatomite blocks, up to a meter long, were wet and slightly consolidated when ejected from the crater or picked up by debris flows from the first eruptions, as shown by the fact that they are plastically bent rather than broken into angular pieces. At 2.4 km from the center of the tuff ring located at the basin edge, the basal tuff breccia contains no blocks of diatomite; however, the matrix of the rock is 20 per cent diatomaceous mudstone. It is possible that the uniform distribution of diatomaceous mud throughout the matrix of the tuff-breccia near the terminus of the

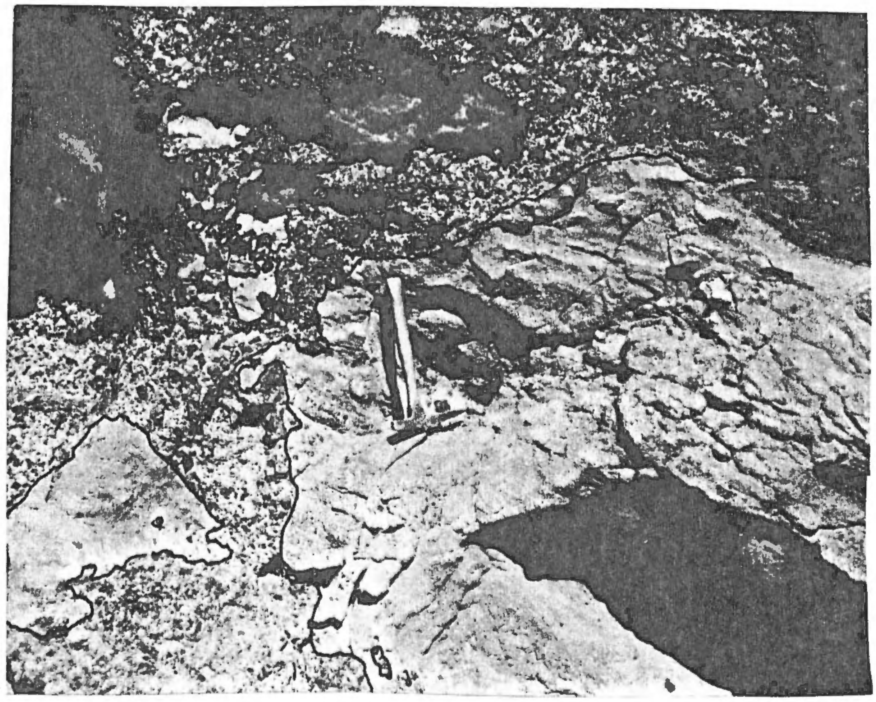


Fig. 30-a. Contact between tuff-breccia of Seven-Mile Ridge and underlying clastic sediments. Central part of the ridge on the west flank. The contact is a very irregular, erosional contact; blocks of the lighter colored clastic sediments have been included in the tuff-breccia.

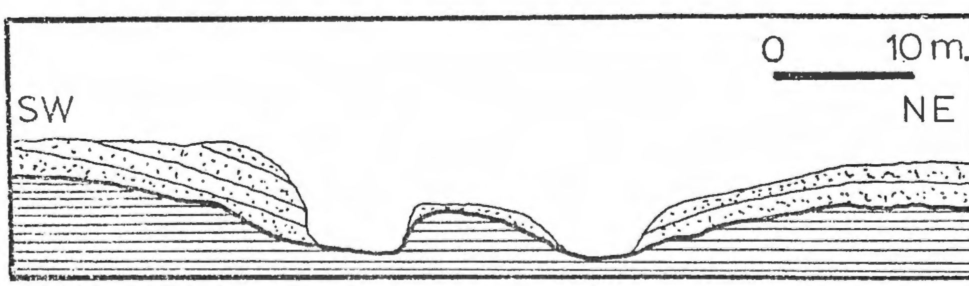


Fig. 30-b. Sediment tuff-breccia contact exposed in a creek on the west side of Seven-Mile Ridge, 1 mile north of the Wagontire Road. The present creek bottom is in the former course of the pre-tuff creek bottom. Stippled layers represent tuff-breccia; horizontal lines represent lake sediments and interbedded silicic air-fall tuffs.

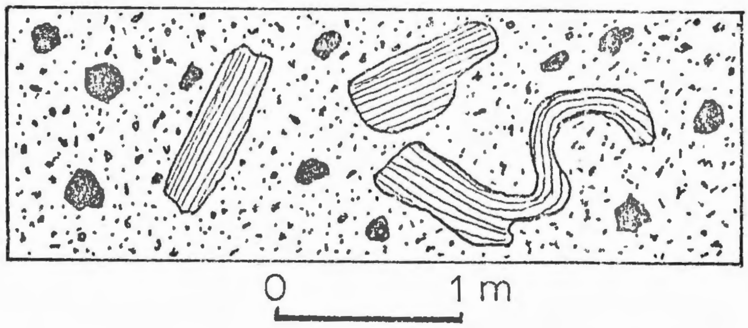


Fig. 31-a. Basal tuff-breccia, Seven-Mile Ridge. This tuff-breccia contains large blocks of plastically deformed lake sediment. Field sketch.

Fig. 31-b. Well-bedded lapilli-tuff, located high on the western slope of Seven-Mile Ridge. These younger deposits unconformably overlie tuffs involved in slumps down the face of the fault scarp which underlies the ridge.

tuff-breccia unit is due to turbulent mixing and disintegration of the blocks as the debris flow moved farther from the vent.

The southernmost tuff rings in Seven-Mile Ridge, located above the former lake level, consist mostly of moderately well-bedded, partly palagonitized sideromelane lapilli-tuffs which contain 1 to 2 per cent basalt blocks and bombs. The color ranges from dark yellow-brown for tuff on the outer flanks to brown-orange for tuff beds near the vent areas. The beds, 2.5 mm to 0.7 m thick, can be traced for several hundred meters in some cases without any noticeable change in thickness (fig. 31-b) and commonly show graded bedding.

The largest tuff ring is located along the axis of Seven-Mile Ridge, slightly above former lake level, and is the only tuff ring with the crater partly preserved. It is about 3 km in diameter and 240 m high at this northern crest. Beds within the eastern rim of the ring have an overall anticline-like structure, although there are small synclinal structures on the crest. This wavy pattern probably developed by draping of the tuff into gullies which were eroded into the sides of the ring between periods of eruptive activity (cross-section B-B', pl. 10).

The western half of the largest tuff ring in the complex overlies a fault scarp, which decreases in height from 61 m at the southern end to below lake sediment level at the northern end. Immediately west of the buried fault scarp the tuff beds are deformed by slumping down the scarp. The slumped beds in turn are overlain by beds derived from a small vent which opened up along the buried scarp.

At several localities in the largest tuff ring there are slight disconformities between the tuff layers as shown by the presence of interbedded sandstone and white silicic air-fall tuff layers. Thus, there were at least two periods of eruptive activity from the largest ring which involved a time interval long enough for several feet of clastic sediment to accumulate.

Vent areas in all of the tuff rings are filled with lapilli-tuff and alluvium. In all except the largest tuff ring, vent locations were determined by attitudes on bedding planes and inward-dipping unconformities. Bedding, however, is well preserved in only the southern vent areas. The absence of bedding in most of the craters, or vent areas, is apparently caused by alteration of sideromelane to palagonite by late stage hydrothermal activity and by later weathering. Original bedding becomes unrecognizable with the breakdown of tuff particles to a uniform particle size.

A vertical tuff dike, 2 to 3 meters thick and 91 meters long, cuts sharply across tuffs near the center of the southernmost tuff ring (fig. 32). This dike consists of massive lapilli-tuff, containing 10 to 15 per cent blocks of bedded lapilli-tuff and angular basalt.

There are three intersecting basalt dikes at the southwest edge of the largest ring. They thicken from 0.5 meter at the extremities to 6.2 meters where they join. They consist of fractured, aphanitic, olivine-bearing basalt. Tuffs adjacent to the dikes have been altered to brittle, orange-brown rock.

The east flanks of the two northernmost rings are buried by well-bedded gravel deposits. The gravels were deposited during the leveling of the northern tuff rings by wave action. These consist of well-rounded clasts of cemented palagonite tuff. Imbricated cobbles and pebbles are interbedded with moderately well-sorted sand. Some of the sandy beds contain an abundance of small gastropods and pelecypods(fig. 33).

FLAT TOP

Flat Top is located 3.2 km west of the Cabin Lake Ranger Station, just beyond the north edge of Fort Rock Valley. The ring is 1520 meters in diameter and 61 meters high.

Fig. 32. Tuff dike which cuts well-bedded tuffs of the southernmost ring in the Seven-Mile Ridge tuff ring complex. Small fragments of the slightly darker bedded lapilli-tuff are included in the lapilli-tuff of the dike.

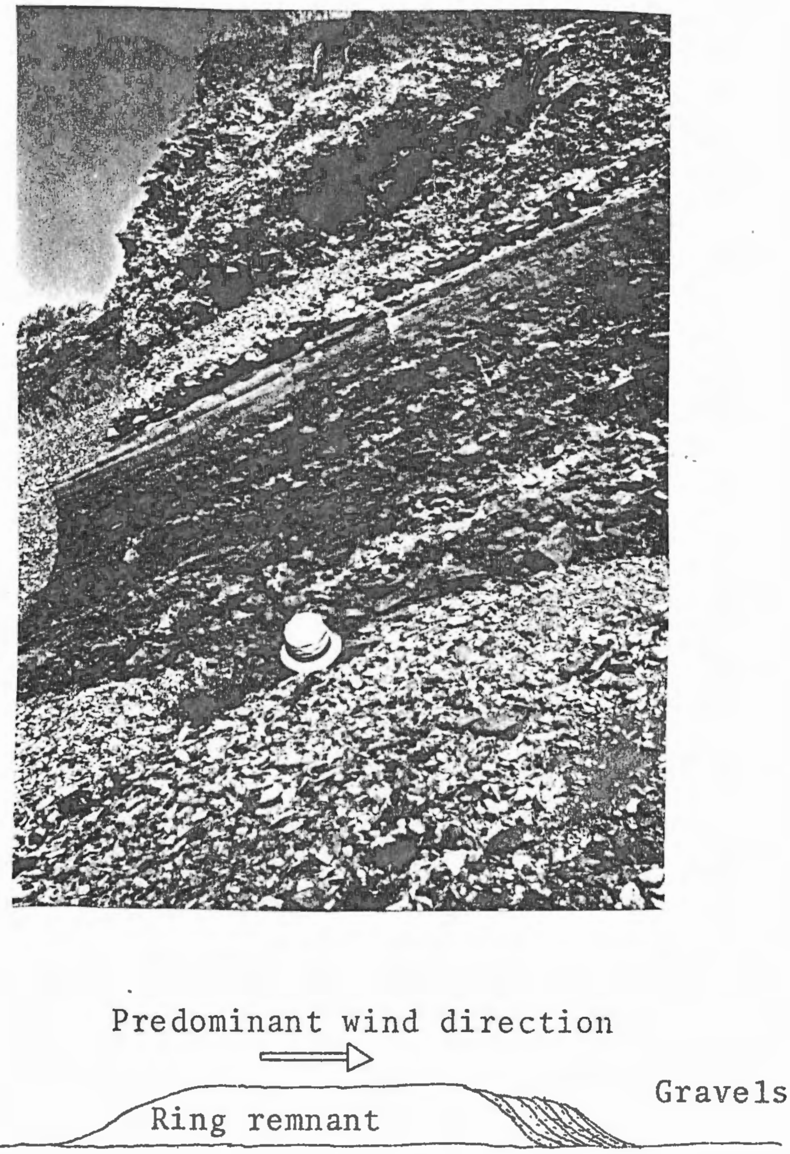


Fig. 33. Well-bedded gravel and sand located on the eastern, outer edge of northern Seven-Mile Ridge. The cobbles and pebbles consist of well-cemented palagonite tuff eroded from the tuff rings which make up the ridge. The gravels are located only on the east side of the ridge, indicating that waves generated by winds from the west or southwest deposited the gravels on the lee side of the rings (see sketch).

Fig. 34. Oblique aerial photograph of Flat Top. View is north. Exposures of light yellow-brown tuff are visible on the slopes of the tuff ring. The crater was filled with a lava lake, the surface of which gives the volcano its name. Lava flowed down the slope to the left side.

The ring consists of moderately well-bedded sideromelane lapilli-tuff, with some pod-shaped interbeds of tuff-breccia. Beds of lapilli-tuff are 3 mm to a meter thick. Some lapilli-tuff beds are graded upward from lapilli to fine tuff size. Bedding plane sags, formed by impact of blocks onto the ring slopes, are present in the finer-grained tuff beds.

The ring is a simple, circular, anticline-like structure. The only deviation from this is a small slump structure on the southwest side, where tuff beds have been piled up into a broad, low anticline.

After formation of the ring, the crater was filled with lava; the former lava lake is now exposed in 12 to 14 meter high cliffs around the summit of the hill. Lava spilled over the northwest edge of the ring forming a 3 meter thick flow which reaches the base of the ring.

The east side of the former lava lake is cut by normal faults 1 to 4 meters high, with blocks downthrown toward the outer edge. The faulting is due to slumping of the outer parts of the ring and the overlying basalts of the former lava lake.

TUFF RING IN THE LOST FOREST

This ring remnant is located in the Lost Forest area at the northeast corner of Christmas Lake Valley. It is a crescent-shaped ridge 640 meters long and 46 meters high (fig. 35). Only the eastern half of the ring crops out. The western half was eroded away and subsequently buried by recent sand dunes.

The ring remnant is composed of well-bedded sideromelane lapilli-tuff in beds 1 cm to 30 cm thick. Beds can be traced for over a hundred meters without any noticeable change in thickness. Many of the beds are graded, from lapilli to fine tuff size. The few basalt blocks range from 30 cm to 1 1/2 meters in diameter, with average size increasing closer toward the western, or crater side of the ring.

An unconformity dips west at an angle of 30 degrees into the crater area (fig. 35). The unconformable surface is smooth and has a sharp contact with overlying tuffs. The intersection between the unconformity and ring crest, which existed before the ring had reached maximum size, is buried by tuffs which continue over the crest and onto the eastern slope (fig. 35).

EARLIER PLIOCENE TUFF RINGS

Beyond the edges of Christmas Lake Valley, are 10 tuff rings and one tuff cone interbedded with lacustrine and fluvial sediments of Pliocene age. Most of these rings are poorly exposed, having been partly buried by extensive basalt flows. Most were exhumed by erosion after faulting and uplift of Pliocene rocks. Three groups

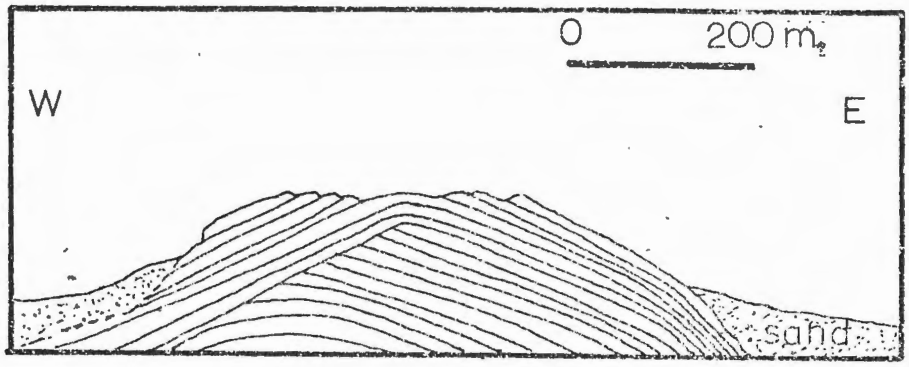


Fig. 35-a. Cross-section of the tuff ring in the Lost Forest. Only the eastern half of the ring remains. The original shape of the crater and ring cannot be determined because of burial by wind-blown sand.

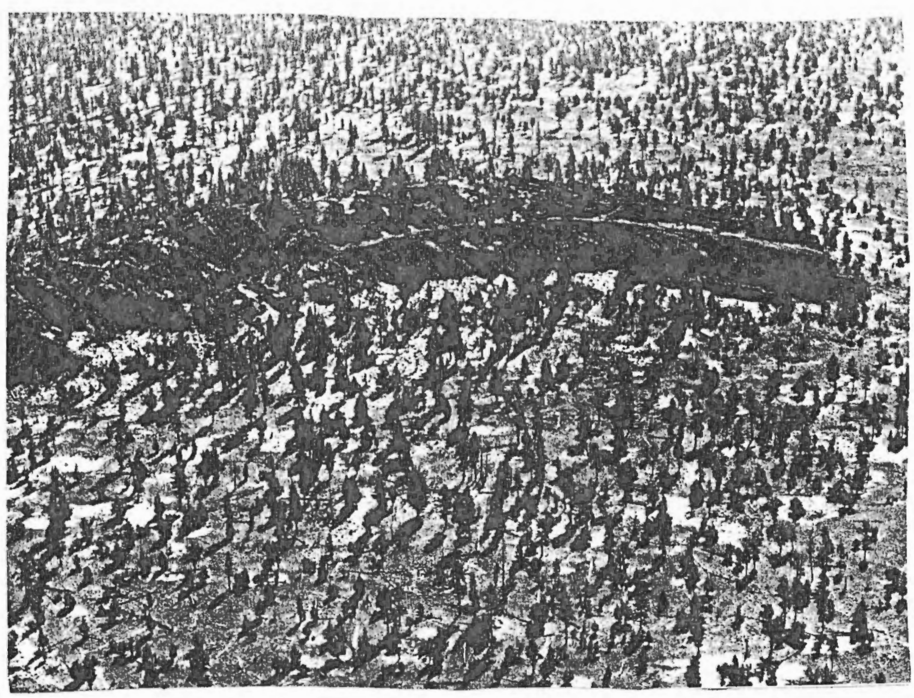


Fig. 35-b. Oblique aerial photograph of the tuff ring in the Lost Forest; taken from the west side of the ring.

of rings were mapped: (1) Those located just beyond the eastern edge of Christmas Lake Valley (E-1 to E-4); (2) those located just beyond the southeast corner of Christmas Lake Valley; and (3) those in Fandango Canyon – St. Patrick Mountain complex. Features of these rings are summarized in the following chart. Locations are on figure 2.

SIDEROMELANE TUFF

The major component of the vitric tuffs of the tuff rings is clear, light to medium brown (in thin section) sideromelane. The unaltered sideromelane normally contains only a few feldspar microlites in addition to feldspar and olivine phenocrysts.

The sideromelane fragments have straight or slightly curved edges (fig. 36), particularly the blocky, nonvesicular fragments. The edges of grains are scalloped where broken by the outermost vesicles. No fluidal shapes of droplets or broken droplets, characteristic of ash-size ejecta from cinder cones, were found in the tuffs of the tuff rings studied. Blocky glass fragments, usually less than 50 microns long, make up the matrix of the tuffs (appendix 3).

The average vesicularity (data gathered by using a microscope and image analyzing computer) for the vesicular sideromelane grains is about 20 per cent, with average

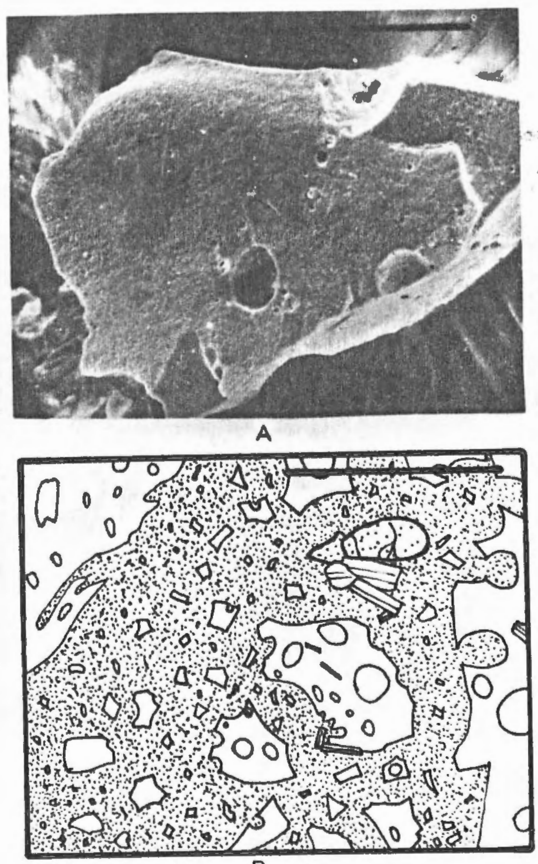
Table 1. Tuff Rings and Cone of Pliocene Age: A Summary.

NAME	SIZE	BEDDING	ROCKS	REMARKS
E-1	1200 m diameter	Massive	Palagonitized sideromelane tuff	Very poorly exposed.
E-2	2130 m diameter, 15 m high at crest	Poorly bedded lapilli-tuff	Partly palagonitized sideromelane tuff	990 m wide crater, partly filled with mudstone and alluvium.
E-3 (younger)	The ring remnant has a radius of about 1400 m	Well-bedded lapilli-tuff	Sideromelane lapilli-tuff with a few blocks of basalt and cemented tuff	The tuff beds exhibit bedding plane sags and cross-bedding with current directions radial around the crater area. An unconformity dips into the crater area at an angle of 40°; it is covered with well-bedded lapilli-tuff.
E-3 (older)	Unknown	Moderately well-bedded tuff and lapilli-tuff	Palagonite tuff	There are some graded beds with accretionary lapilli at the base. This is an older ring, exposed in the cliff face below E-3 (younger). The two rings are separated by 20 m of basalt; part of a flow which buried the older ring.
E-4	2280 m in diameter	No good exposures	Palagonite tuff	Very poorly exposed.
SE-0	Not known; partly buried by lake sediments	Massive	Lapilli-tuff and tuff-breccia. Sideromelane, partly altered to palagonite	2 to 5% angular blocks of basalt, up to 1.1 m long.
SE-1	3.21 km in diameter, 61 m high at the crest	Well-bedded, 2 mm to 0.6 m thick beds of lapilli-tuff and tuff	Sideromelane tuff	Contains 5 to 15% blocks of aphanitic basalt and mudstone, up to 5 cm in diameter. Graded bedding and cross-bedding present.
St. Patrick Mountain	2000 meter diameter at the base. 180 m high	Poorly bedded lapilli-tuff	Palagonitized sideromelane tuff in the cone. Aphanitic basalt in the former lava lake and dikes	A 2 m wide, vertical dike extends north for 1800 m from the lava lake at the cone crest.
Tuff Ring in Fandango Canyon	2600 m in diameter. 30 to 90 m high at the crest	Well-bedded lapilli-tuff in beds 2 to 10 cm thick and poorly bedded lapilli-tuff in beds up to 2 m thick	Sideromelane tuff	An unconformity dips into the crater at an angle of 37°. The unconformity is covered with well-bedded tuffs.

Fig. 36. Examples of sideromelane hyaloclastic tuff from Tuff Ring 2, Table Rock tuff ring complex.

A. Scanning electron photomicrograph of a blocky sideromelane fragment. The shape of the fragment and the low vesicularity are characteristic of ash from all of the tuff rings in the Fort Rock - Christmas Lake Valley Basin. The scale is 0.1 mm long.

B. A sketch of a thin section of tuff consisting of nearly all light brown, clear sideromelane fragments in a fine-grained matrix of glass fragments. A few phenocrysts of calcic plagioclase and olivine are visible in the upper right corner of the sketch. The large sideromelane lapillus in the upper left corner has a 0.4 mm thick accretionary coating of very fine-grained vitric ash. The scale is 1 mm long.



A

B

vesicle sizes ranging from 40 to 280 microns in diameter. The range of vesicle diameters is from less than 1 micron to approximately 500 microns. This range is similar to that of the ash from the cinder cones located outside of the former lake basin. The average ratio of nonvesicular to vesicular plus nonvesicular glass of all tuff ring samples studied is approximately 0.5; the average ratio for ash size particles from the cinder cones is 0.0. Vesicles in the hyaloclastic sideromelane fragments are usually spherical and are rarely drawn out by flow or stretching during ejection from the vent, which is often the case in ash from magmatic eruptions that form cinder cones.

The blocky vitric ash fragments, with straight or slightly curved grain edges, are characteristic of the juvenile ejecta from the tuff rings. The fragments appear to have formed by contraction and shattering of the glass formed when the magma was quenched on contact with large volumes of water. Bubble growth within the magma was stopped, resulting in the high ratio of nonvesicular glass fragments to the total glass component, in contrast to all vesicular vitric ash from magmatic eruptions which formed cinder cones.

ACCRETIONARY LAPILLI

Sideromelane fragments with accretionary coats of finer-grained tuff are common, especially in normally graded beds in the rings. The accretionary coats show little concentric banding; the coatings are so fine-grained as to be nearly opaque in thin section (fig. 37). In out-crop, the lapilli look like gray or brown mud balls until broken open, exposing the sideromelane nuclei and, in some cases a very poorly defined concentric banding. Moore and Peck (1962) describe both recent and ancient accretionary lapilli from many localities in the western United States:

> p. 188. "Typically each lapillus has a core consisting of unlayered, relatively uniform fine ash, which forms from one-eighth to one-third of the lapillus. The grain size and composition of the material in the core of the lapilli are similar to that of the matrix which surrounds the lapilli; indeed, where matrix and core are in contact in broken lapilli, the two may be almost indistinguishable, although slight differences in grain size and color usually indicate the boundary."

According to Moore and Peck (1962), most of the accretionary lapilli were formed by accretion of moist ash in eruptive clouds and fell as mud-pellet rains. This is similar to the growth of a hailstone in a storm, which picks up layer after layer of water, which in turn freezes as the hailstone is carried up and down, until the mass is too large to be carried.

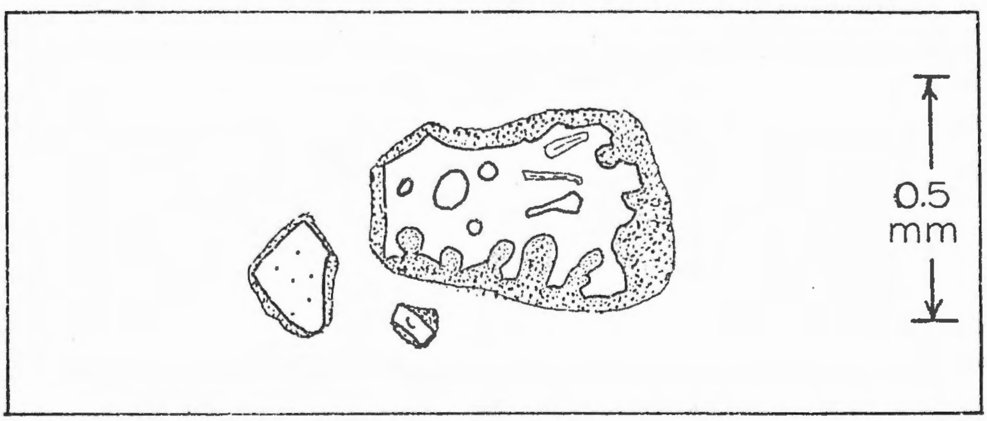


Fig. 37. Sketch of typical accretionary lapilli as they appear in thin section. Vesicular and nonvesicular sideromelane fragments and olivine and feldspar crystals have thin coats of very fine-grained dust.

Deposits of accretionary lapilli are also present in cross-bedded tuff units. It is most likely that the cross-bedded tuff beds were deposited by currents moving away from the vent. The origin of the cross-bedding is discussed in a later section. The accretion process, forming accretionary lapilli, could occur either in air-fall from the eruption cloud or in ash-laden steam clouds moving across the ground surface.

ALTERATION OF SIDEROMELANE TO PALAGONITE

Introduction

Sideromelane bearing tuffs in nearly all of the tuff rings of the Fort Rock - Christmas Lake Valley Basin are partly or completely altered to yellow or orange-brown palagonite.

The term *palagonite* was first used by von Waltershausen (1853) in Sicily at Portella di Palagonia to describe "an amber-yellow to collophane-brown substance" closely associated with water free basaltic glass called sideromelane.

Tuffs Within Vent Areas or Craters

In crater areas at tuff rings 1 and 2, Table Rock tuff ring complex, southwest Green Mountain, the largest tuff ring in the Seven-Mile Ridge complex and in parts of Fort Rock and Moffitt Butte, the tuffs are completely altered to orange-brown palagonite. Beyond the crater areas, tuffs are slightly altered. The contacts between completely and slightly palagonitized tuffs are relatively sharp. Samples were collected, wherever possible, from beds which could be traced across the contact between palagonitized and unpalagonitized tuffs. In this way, ash from the same bed and of the same composition could be studied in different stages of alteration to palagonite (Table 2).

In thin section, shards in slightly altered sideromelane tuffs are rimmed with palagonite. Most of the fine-grained glassy fragments of the matrix are also altered. The rims of sideromelane fragments are clear, yellowish-orange to orange and are isotropic, similar to the gel-palagonite described by Peacock (1926)(fig. 38-b). The boundary between the unaltered core of the sideromelane fragment and the palagonite rim is sharp. Usually, the palagonite rim is of uniform thickness. In some cases, a glass fragment may be unaltered if surrounded by a very fine-grained matrix. Vesicular sideromelane fragments, if in the permeable base of a graded bed with little matrix, may be completely altered to palagonite; whereas shards surrounded by matrix are only partly altered. There are traces of zeolite and calcite cement, increasing with the increase in palagonite.

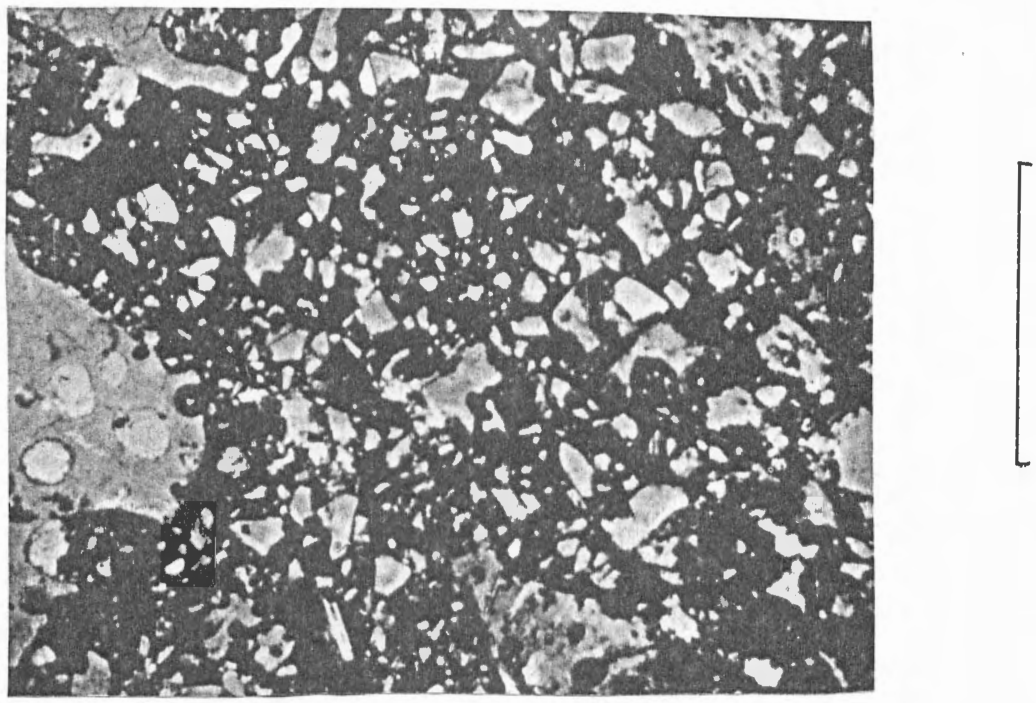


Fig. 38-a. Unaltered sideromelane tuff. Scale is 1 mm long.

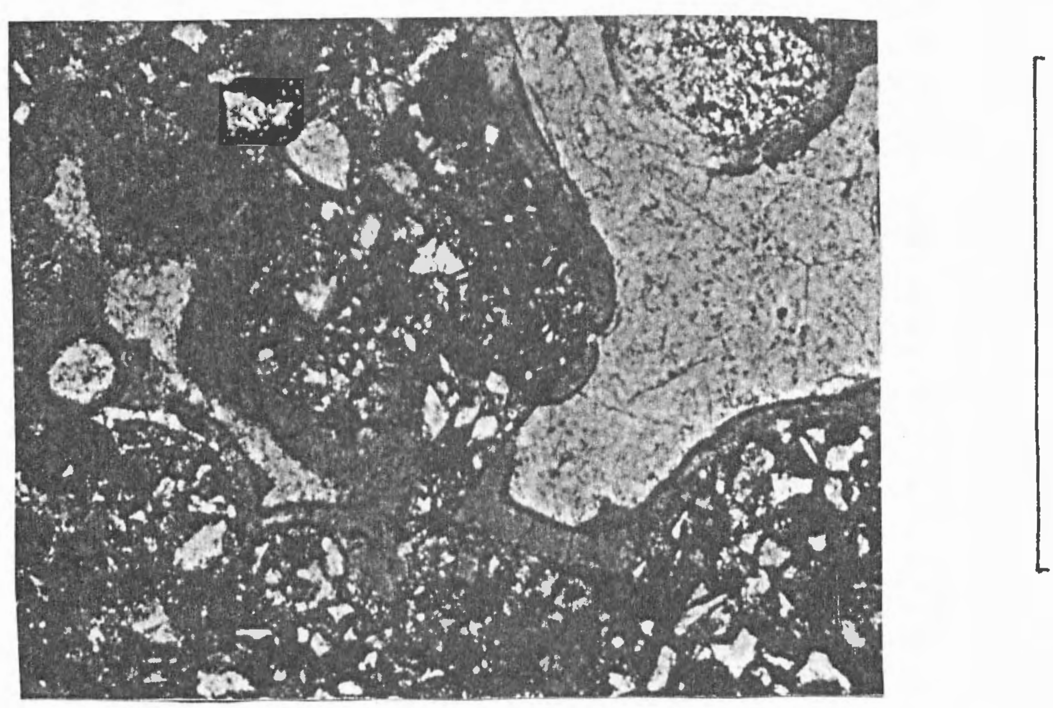


Fig. 38-b. Slightly altered sideromelane tuff. Sideromelane fragments are rimmed with orange-brown palagonite. Scale is 0.5 mm long.

In highly altered tuffs of the crater areas, the palagonite is banded, from gel-palagonite near the center of the fragment (or sideromelane core, if one still exists), to radially fibrous, slightly birefringent, dark orange palagonite in the outer parts of the grain (fig. 38-c). The fibrous palagonite is the fibro-palagonite of Peacock (1926). Interstices between the grains are filled with calcite and zeolite cement, generally phillpsite.

Tuffs in which the cores of sideromelane grains are completely gone are broken by cracks similar to dessication cracks. After cracking, the fragments are broken down to 10 to 40 micron diameter particles. Completely altered, the end product of palagonitization is a massive rock consisting of fine-grained clays, zeolites, iron oxides and calcite (fig. 38-e).

Several chemical analyses of tuff in different stages of palagonitization were made (table 2). The most noticeable change is the increase of total water content from 1 to 3 per cent for sideromelane tuff to 10 to 18 per cent for palagonite tuff. There is considerable loss of silica, calcium and sodium. Hay and Iijima (1968) view the process of palagonitization as either a process of hydrogen-ion metasomatism or of replacement of metallic oxides in glass by water molecules.

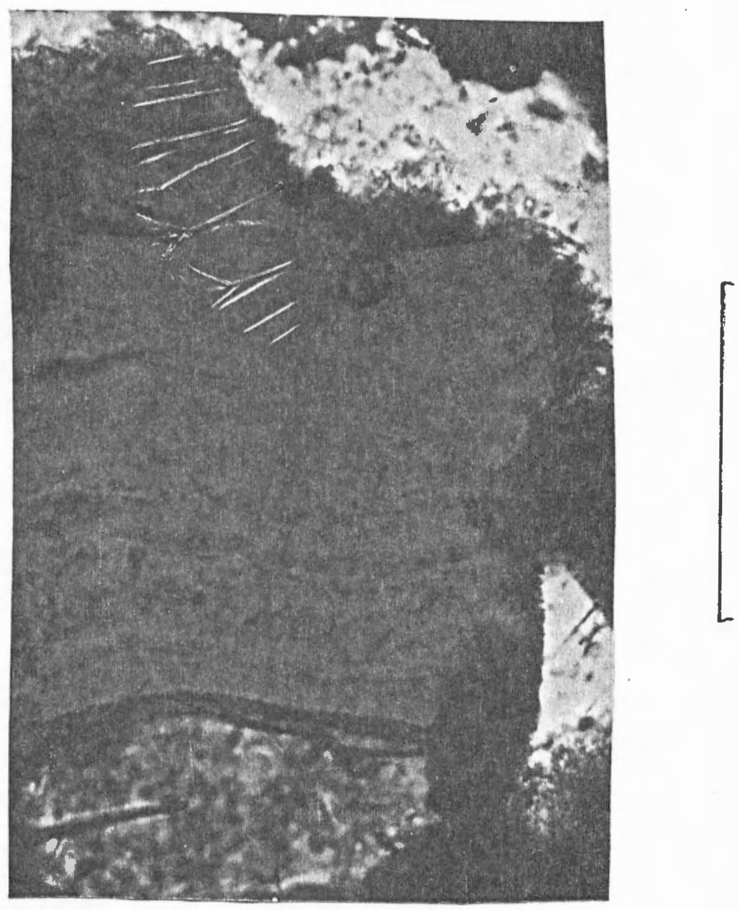


Fig. 38-c. Edge of a sideromelane fragment, showing banded "fibro-palagonite." The sideromelane-palagonite contact is sharp. Palagonite at the contact is medium orange, grading outward into dark reddish-orange palagonite at the outer edge of the grain. Scale is 0.1 mm long.

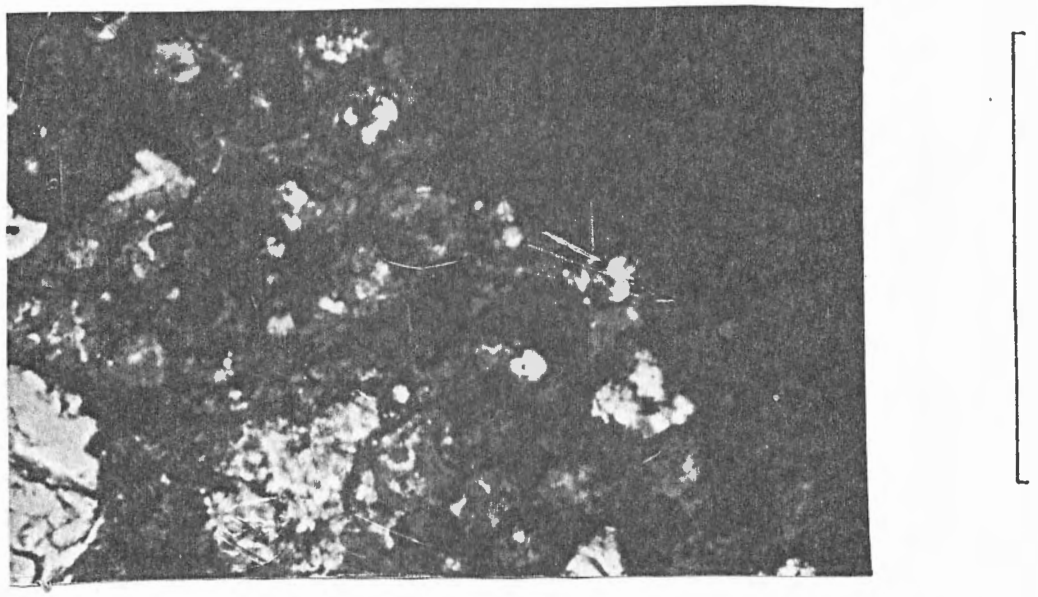


Fig. 38-d. Photograph of a completely palagonitized vesicular sideromelane fragment. Interstices and vesicle cavities are filled with zeolite and calcite cement (white areas in the photograph). Scale is 0.5 mm long.

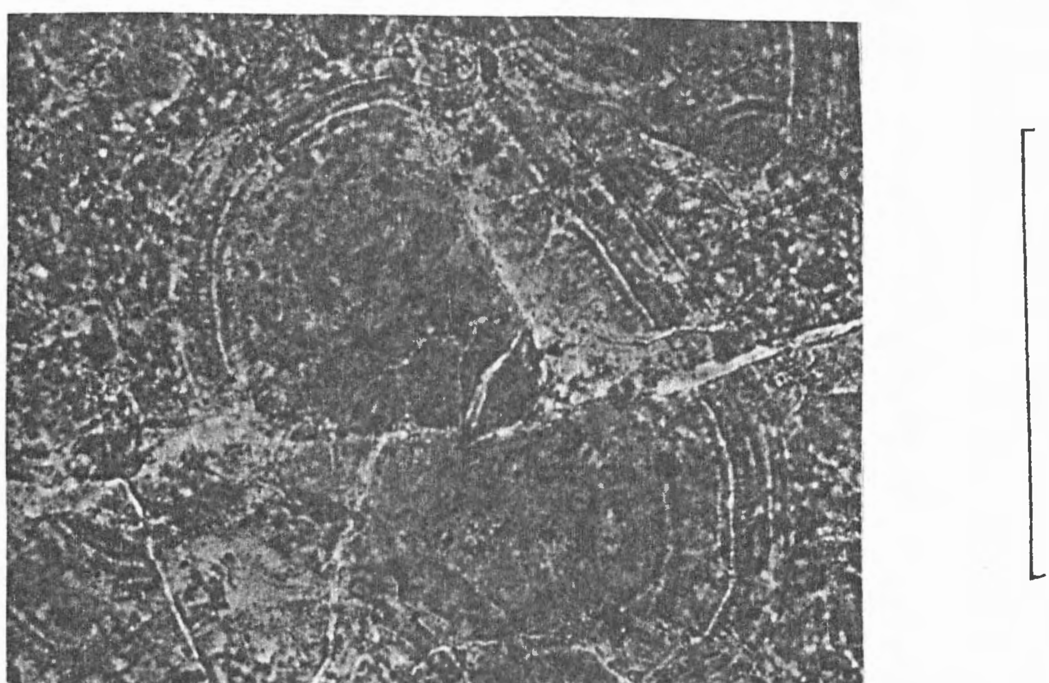


Fig. 38-e. Photograph of a completely palagonitized sideromelane fragment. The banded areas are "fibro-palagonite." Dessication cracks cut across the fragment. Scale is 0.1 mm long.

CHEMICAL CHANGES DURING ALTERATION OF SIDEROMELANE TO PALAGONITE (BULK SAMPLES):

No.	1*	2*	gain-loss	3*	4*	gain-loss	5*	6*	gain-loss
SiO_2	47.92	43.60	-4.32	49.98	44.99	-4.99	45.03	47.35	+2.32
Al_2O_3	12.24	10.56	-1.68	13.69	11.08	-2.61	12.15	12.02	-0.13
FeO (total)	9.12	8.27	-0.85	9.96	9.28	0.68	11.53	11.71	+0.18
MgO	8.45	6.71	-1.74	6.54	5.37	-1.17	8.24	5.03	-3.21
CaO	10.89	9.53	-1.36	9.75	8.63	-1.12	10.13	8.22	-1.91
Na_2O	2.41	0.46	-1.95	3.03	2.11	-0.92	2.04	3.00	+0.96
K_2O	0.40	0.34	-0.06	0.68	0.61	-0.07	0.43	0.72	-0.29
H_2O+	2.0	10.20	+8.20	0.6	6.90	+6.3	4.6	6.8	+2.2
H_2O-	2.0	7.80	+5.80	1.2	7.10	+5.9	3.4	3.0	-0.4
TiO_2	1.03	1.26	+0.23	1.28	1.32	+0.04	1.75	1.76	+0.01
MnO	0.16	0.16	0.0	0.18	0.16	-0.02	0.20	0.20	0.0

*CO_2 not measured.

1. Sideromelane tuff from SW Green Mountain. 2. Palagonite tuff from SW Green Mountain. 3. Sideromelane tuff from Moffitt Butte. 4. Palagonite tuff from Moffitt Butte. 5. Inner "core" of talus block from Big Hole; sideromelane tuff. 6. Outer patina of orange palagonite on same block as no. 5.; slightly palagonitized. Analyses made according to the methods of Adler (1966) and Shapiro & Brannock (1962). X-ray flourescence analyses are by the author.

Table 2

The elements lost during reaction of sideromelane with water or steam are those necessary for the precipitation of zeolite and calcite cement in open interstices between grains.

The sequence of alteration of a sideromelane fragment to palagonite appears to be as follows:

1. The formation of rims of gel-palagonite on sideromelane grains; original fragment shape is maintained.

2. The inward migration of the sideromelane – palagonite contact in this grain until the glass is completely altered (palagonitized). Increasing amounts of zeolite and calcite cement are precipitated in open interstices as the alteration of sideromelane to palagonite proceeds.

3. After the complete alteration of sideromelane to palagonite, cracks begin to develop in the palagonite grains which in turn disintegrate into fragments bounded by the cracks. In the final step, bedding is destroyed by the reduction of all the altered grains to fine-grained palagonite fragments; eliminating grain size differences necessary to define bedding planes.

Slightly altered sideromelane grains, with thin rims of palagonite, are found in tuff beds outside of crater areas discussed above. This alteration appears to be due primarily to weathering.

Tachylite fragments present within the tuff were not altered by weathering or mild hydrothermal activity. The stability is apparently due to tachylite being sub-microcrystalline, with very little unstable glass.

Localization of intensely altered palagonite tuffs in some of the crater areas suggests that the alteration was due to the reaction of sideromelane tuffs with steam seeping through the ejecta. Steam may have come from slow seepage of lake or ground water into the vent to form a short-lived hydrothermal system, but in amounts too small to clear the conduit of debris. Palagonitization by mild hydrothermal activity has been described by Sigvaldason (1968) in Icelandic tuff rings.

DIKES, FLOWS AND LAVA LAKES ASSOCIATED WITH THE TUFF RINGS:

The craters of the tuff rings at Table Rock, Table Mountain, Flat Top, Southwest Green Mountain, the small ring at Moffitt Butte and St. Patrick Mountain all contain some cinder beds and small lava lakes. Only the crater lakes at Flat Top and Table Mountain overflowed, sending lava flows down the sides of the tuff rings. It appears that the magmatic eruptions, consisting of the ejection of cinders and ash, followed by lava flows, began when surface or ground water had been sealed off from the vent. These flow rocks are very useful for comparing the magmas which formed the tuff rings with the magmas which formed cinder cones and flows beyond the edges of the lake basin at that time (table 3).

Samples from the Table Mountain and Table Rock lava lakes and from flows from a large cinder cone immediately east of Hogback Butte on the northern side of the Fort Rock basin consist of small phenocrysts of feldspar (An_{55-65}) and olivine in a submicrocrystalline or tachylitic groundmass. Some of the olivine and feldspar phenocrysts are grouped together in small clots. The total percentage of phenocrysts ranges from 8 to 17 per cent (appendix 2).

Higher percentages of phenocrysts (20 to 60 per cent) are characteristic of the lavas at Flat Top, the dike at Horning Bend, Moffitt Butte, the dike at Seven-Mile Ridge and the Devil's Garden lava flow (located north of the edge of the Fort Rock Basin). As in the lavas at Table Mountain and Table Rock, these lavas consist of 0.3 to 0.5 mm long feldspar phenocrysts (An_{55-65}), olivine phenocrysts, and, at Seven-Mile Ridge, clinopyroxene phenocrysts, in a finely crystalline or tachylitic groundmass. In samples where the groundmass minerals are large enough to be identified, it consists of plagioclase, olivine, opaque minerals and glass.

The phenocrystal mineralogy of the lavas is very similar to the phenocryst assemblages of the tuffs (appendix 2): mostly feldspar (An_{55-65}) with some olivine and traces of clinopyroxene or orthopyroxene. Generally, it appears that the magmas which fed the eruptions at vents located along fault trends which cross the Fort Rock – Christmas Lake Valley Basin were similar; the volcanic features are, however, different, with tuff rings and cones located in and near the former lake basin, and cinder cones with associated lava flows located beyond the perimeter of the basin.

The chemical composition of basalts from the lava lakes at Flat Top and Table Rock, the dike at Seven-Mile Ridge, and a lava flow from Lava Mountain are compared in Table 3. When plotted on the diagrams of Al_2O_3 - total alkalis - SiO_2 relations of tholeiitic, high-alumina, and alkali basalts of Kuno (1960, p. 127), the basalts of the Fort Rock - Christmas Lake Valley Basin fall within the high-alumina basalt fields. They are similar in composition to the high alumina basalts of the Modoc Lava-Bed Quadrangle, Crater Lake, and Lassen Peak Areas, (southern Oregon and northern California)(analyses from Kuno, 1960). Shoemaker (1962) proposed that phreatomagmatic eruptions were rare and that most maar volcanoes, especially those of the Eifel and Hopi Buttes are formed by alkalic magmas rich in water and other volatile constituents. He proposes that the gas phase in the maar-forming eruptions

Table 3. Chemical analyses of basalts from the Fort Rock – Christmas Lake Valley Basin, compared with analyses of High-Alumina basalts from northern California.

Sample No.	1	2	3	4	5	6
SiO_2	50.54	50.34	50.67	52.39	47.26	51.46
Al_2O_3	16.18	15.67	17.28	16.02	18.56	17.69
FeO (total)	10.03	10.82	10.87	8.49	9.38	10.42
MgO	6.63	8.08	7.05	6.48	9.62	5.13
CaO	9.90	10.33	10.12	9.73	11.54	8.92
Na_2O	2.70	3.09	2.42	3.33	2.24	3.37
K_2O	0.59	0.39	0.39	0.86	0.20	0.77
H_2O+	0.2	0.0	0.0	0.8	0.3	0.44
H_2O-	0.2	0.3	0.6	0.6	0.06	0.3
TiO_2	1.37	1.68	1.37	1.23	0.88	1.25
MnO	0.19	0.19	0.19	0.16	0.08	0.18
Total	98.53	100.9	100.95	100.09	100.2	100.07

1. Basalt flow in the lava lake of tuff cone 3, Table Rock tuff ring complex. Analysis by the author.

2. Lava lake in the crater of the north tuff ring, Table Mountain. Analysis by the author.

3. Basalt from a dike which crosses the largest tuff ring in the Seven-Mile Ridge tuff ring complex. Analysis by the author.

4. Pahoehoe flow from Lava Mountain. Analysis by the author.

5. Basalt from the Modoc Lava-Bed Quadrangle, California, Analyst, Gonyer (Powers, 1932)(Kuno, 1960).

6. Basalt from the same region as 5, analyst Herdsman, (Powers, 1932)(Kuno, 1960).

may have been derived chiefly, if not entirely, from the basaltic magma.

The maar volcanoes (tuff rings) of the Fort Rock - Christmas Lake Valley basin were formed by high-alumina basalt magmas, not alkalic magmas. As outlined earlier in this study, there is ample evidence that most of the volatiles in the maar-forming eruptions were derived from surface and ground water, not from the magma.

PHYSICAL CHARACTERISTICS OF THE TUFF DEPOSITS

INTRODUCTION

Certain physical characteristics of bedded ash or tuff in the tuff rings can be used to distinguish tuff rings deposited underwater from those deposited subaerially. Massive tuff-breccias are characteristic of underwater tuff rings; well-bedded tuffs, lapilli-tuffs and tuff-breccias--exhibiting cross-bedding, graded bedding, convolute bedding and channels are characteristic of the subaerial tuff rings.

BEDS

Breccia and Tuff Breccia

Most of the subaqueous and some of the subaerial portions of the tuff rings are made up of thick, poorly bedded tuff breccia, in beds 0.5 to 15 m thick. The tuff-breccias consist of angular blocks of pre tuff ring rocks, excavated from the crater or vent by the eruption, in a matrix of sideromelane tuff or lapilli-tuff. Some tuff-breccia beds exhibit crude grading; an example from the Seven-Mile Ridge tuff ring complex contains 65% blocks near the base of the bed and grades upward to 10% blocks near the top of the bed. The lowest beds of tuff-breccia exposed in Tuff Ring 2, Table Rock tuff ring complex, exhibits crude cross-bedding.

The lowest tuff-breccia unit exposed at the Seven-Mile Ridge tuff ring complex can be traced for 2.4 km from the vent area. It is approximately 4.5 m thick close to the vent and decreases to 0.6 m thick at its terminus. Near the vent area, the rock consists of mostly dark brown sideromelane tuff-breccia, with abundant blocks of basalt and contorted diatomite, up to 1 m in diameter (figs. 31-a, 39). 0.8 km west of the vent, the rock contains lapilli-size fragments of diatomite and basalt and is a lighter shade of brown, due to mixing of fine-grained lake sediment into the ash. Near the terminus, the rock characteristic of the tuff-breccia are light gray and consist of mud and diatomite thoroughly mixed with sideromelane fragments. These relations suggest that breakdown and mixing of blocks of lake sediment into the tuff-breccia with increasing distance from the vent area occurred due to turbulent action as it moved across the lake bottom. The contact of tuff-breccia with lake sediments is often irregular, suggesting that some of the blocks of sediment within the tuff-breccia were ripped up as the flow moved across the lake bottom.

Tuff and Lapilli-Tuff

Thin beds which can be traced laterally without any noticeable change in thickness are characteristic of most tuff rings (Russell [1885], Soda Lake, Nevada; Stearns

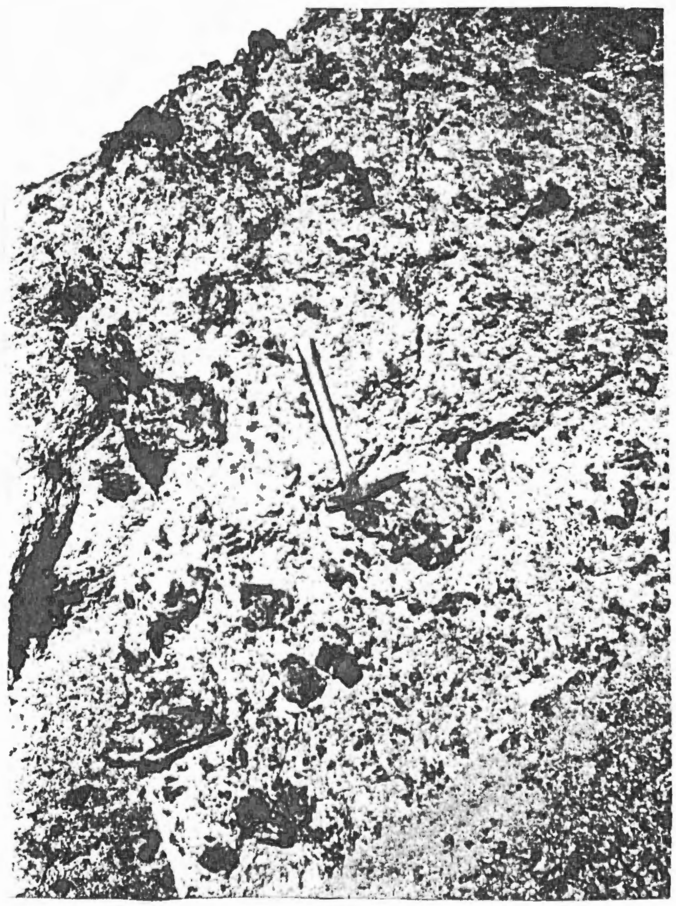


Fig. 39. Tuff-breccia, Seven-Mile Ridge (near the ridge center). Basalt blocks and bombs as well as blocks of lake sediment are included in a matrix of light to dark brown sideromelane tuff.

[1926], Idaho; Wentworth [1926], Hawaii; Shoemaker [1957], Zuni Salt Lake, New Mexico; and Jahns [1959], Pinacates, Sonora, Mexico).

Beds, 1.5 mm to half meter thick, are typical of those parts of the tuff rings which were deposited above lake level; that is, those which were deposited after the tuff rings had been built above lake level, or those constructed along the lake edge. Were it not for the circular, anticline-like form of the rings, it would be easy to misidentify the tuffs in the field as structurally deformed bedded sandstones and silt-stones. These tuff beds can be traced laterally for several hundred meters without any noticeable change in thickness.

Many of the beds are graded. Grading is usually from lapilli-size at the base to fine tuff size at the top of the bed (figs. 40, 41, 45). Lapilli-sized fragments are usually vesicular sideromelane fragments, sometimes with accretionary coats of fine grained tuff. In some instances, for example at southwest Green Mountain, the lapilli at the base of the bed have little or no matrix and an open framework exists.

Much of the graded bedding appears to be due to separation of coarser fragments out of the air-borne eruption cloud, with finer-grained material settling out of the air at a slower rate. Plane beds which exhibit grading

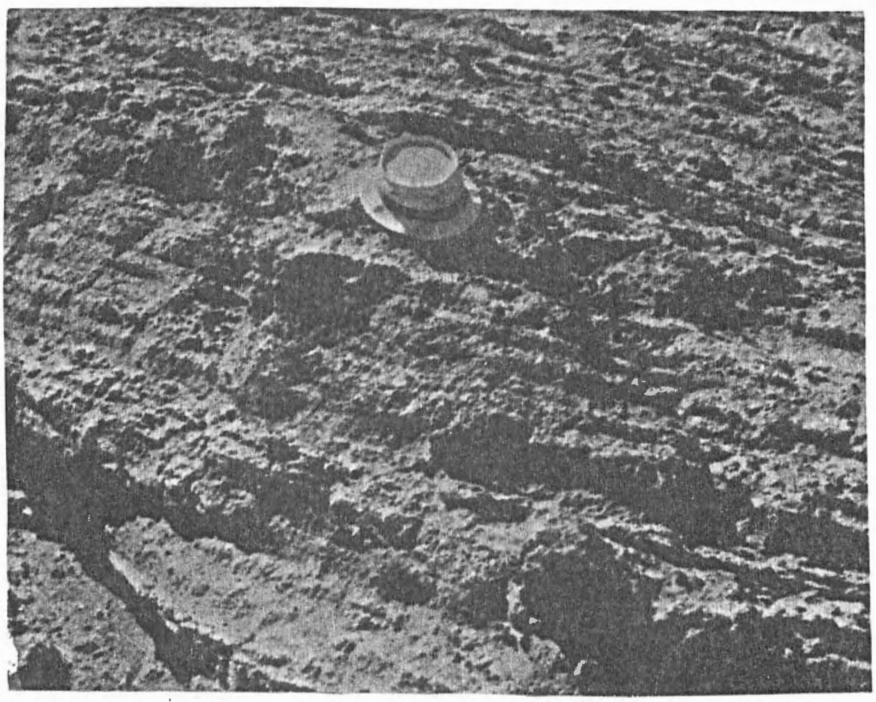


Fig. 40. An outcrop of well-bedded lapilli-tuff, tuff ring 2, Table Rock tuff ring complex. Most of the 1 cm to 15 cm thick beds are graded upward from lapilli to tuff size.

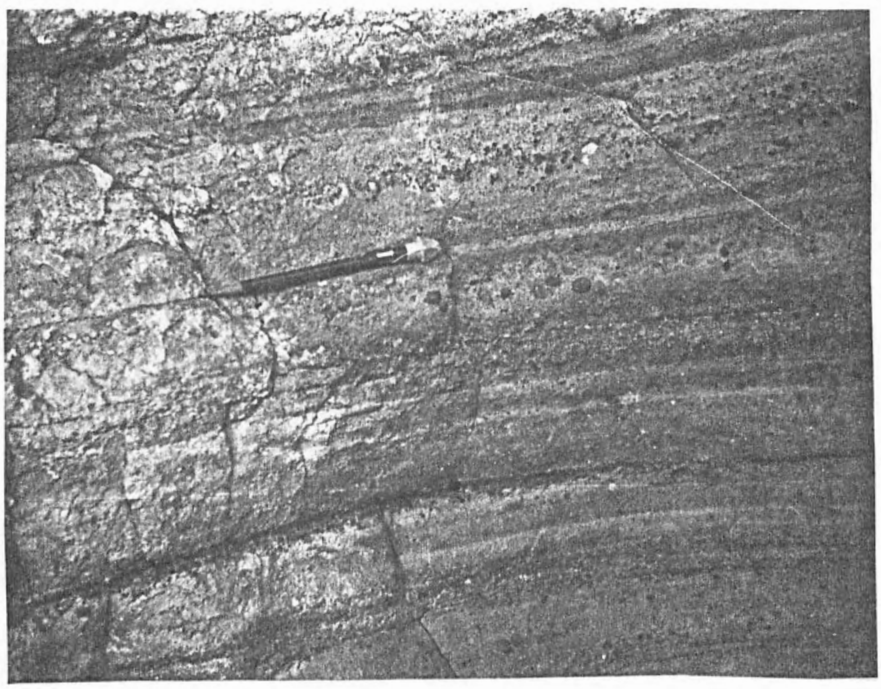


Fig. 41. Well-bedded lapilli-tuff in the tuff ring at Boatwright Ranch. Both normally graded and reversely graded beds are visible. Slightly below and to the right of the pencil are accretionary lapilli.

could be deposited by currents moving down the tuff ring slopes. No criteria were found to be useful in distinguishing graded beds deposited from the air and those deposited by a current moving across the ground surface; excepting situations in which plane-beds of tuff were "plastered" onto near vertical surfaces by ash laden currents moving across the ground surface.

Cross-Bedding

Interbedded with the planar beds at several localities are tabular cross-beds and dunes. Tabular cross-bedding refers to simple cross-bedding where the lower bounding surface is planar and non-erosional. Dune is used as a generic term for ridges of clastic material (sand or ash) which have moved in the direction of the depositing current.

Sets of tabular cross-beds present in the tuff rings are 15 cm to a meter thick (fig. 42). The upper surfaces of the tabular cross-bedded units are flat, parallel to overlying plane beds. In the example shown in fig. 42, the tabular cross-beds are overlain by small dunes which are, in turn, overlain by plane beds. Large scale tabular cross-beds occur within the basal tuff-breccia of tuff ring 2, Table Rock tuff ring complex, on the west side of the ring. Each foreset bed is 1 to 2 m thick; the thickness of the cross-bedded unit is 10 m thick (fig. 5).

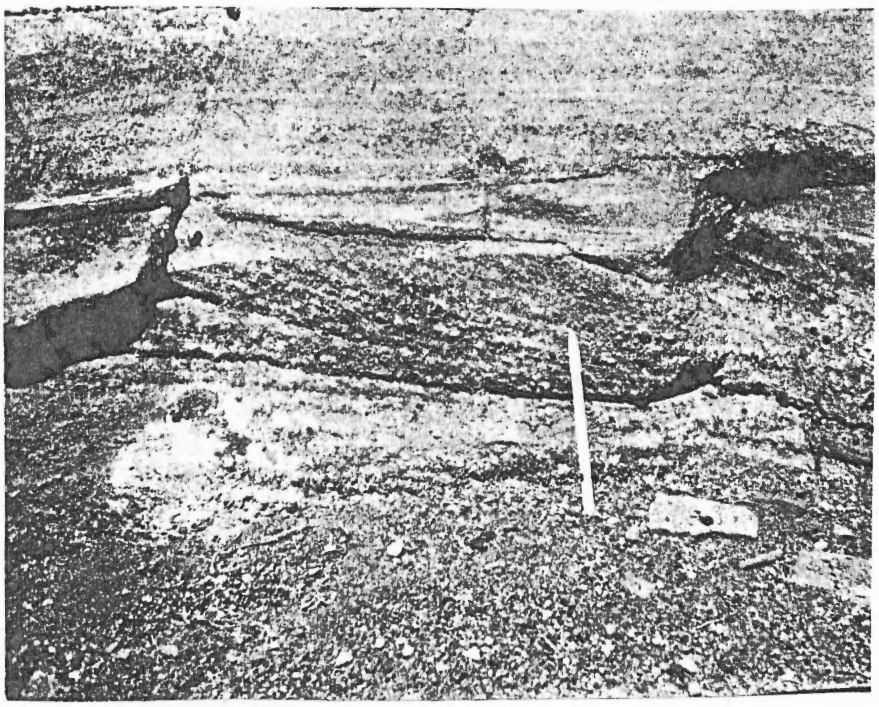


Fig. 42. Tabular cross-bedding in lapilli-tuff of tuff ring E-3 (fig. 1, plate), east end of Christmas Lake Valley. The current direction as indicated by the cross-bedding is from the left to the right; vent area is to the left. The pen in the photograph is 15 cm long.

Two different sets, both with the same current direction are visible in this photograph.

Well-exposed dunes are located on the inner slope of Tuff Ring 2, Table Rock tuff ring complex, where four cross-bedded sets showing dune structures are interbedded with plane beds of lapilli-tuff. The exposed section is about 30 m thick, with dunes in the uppermost 3 m. The average wave length, from crest to crest, is 2 m; the average wave height, from trough to crest is 65 cm (fig. 8). As indicated by cross-bedding within these dunes, they were deposited by a current moving away from the vent. They cannot be attributed to running water because the current directions indicated are upslope.

Cross-bedding at Zuni Salt Lake Crater was attributed by Shoemaker (1957) to fall-out and later aeolian reworking. Saemundson (1967) describes *current bedding* in tuffs at sub-glacial eruptive centers in Iceland which formed once the rings had built up above water level, but ventures no opinion in the English summary as to their origin.

Moore (1967) observed that concentric dune patterns developed around the crater of Taal, Philippines, in 1965, from base surge clouds during the eruption. The base surge clouds are toroidal shaped, turbulent eruption clouds which move away from the base of the vertical eruption cloud. During the eruption of Taal, turbulent mixtures of juvenile ejecta, steam and water moved across the ground surface at hurricane velocity for a distance of

6 km around the crater. Base surge deposits within 3 km of the explosion center are characterized by crude dune-type bedding. Dune crests are oriented roughly at right angles to the direction of movement of the base surges. Fisher and Waters (1969, 1970) have found base surge bed forms in most of the maar volcanoes of the Western United States which are similar to those structures formed during the Taal eruption.

The cross-bedding in the tuff rings of the Fort Rock - Christmas Lake Valley basin, with current directions radial to and directed away from vent areas and, in some cases, directed uphill, was probably formed by base surge clouds and not by wind or running water.

Convolute Bedding

Convolute bedding is defined by Kuenen (1953) as a structure characterized by crumpling or folding of laminations within a well-defined, but otherwise undeformed sedimentation unit. Convolute bedding is present in nearly all of the tuff rings studied. At most places it involves beds ranging from 3 cm thick to several meters thick (fig. 43). The exception to this range of thicknesses is a large-scale slump feature involving a sequence of beds 61 m thick (fig. 6), at Tuff Ring 1, Table Rock tuff ring complex. Axial planes of overturned anticlines and

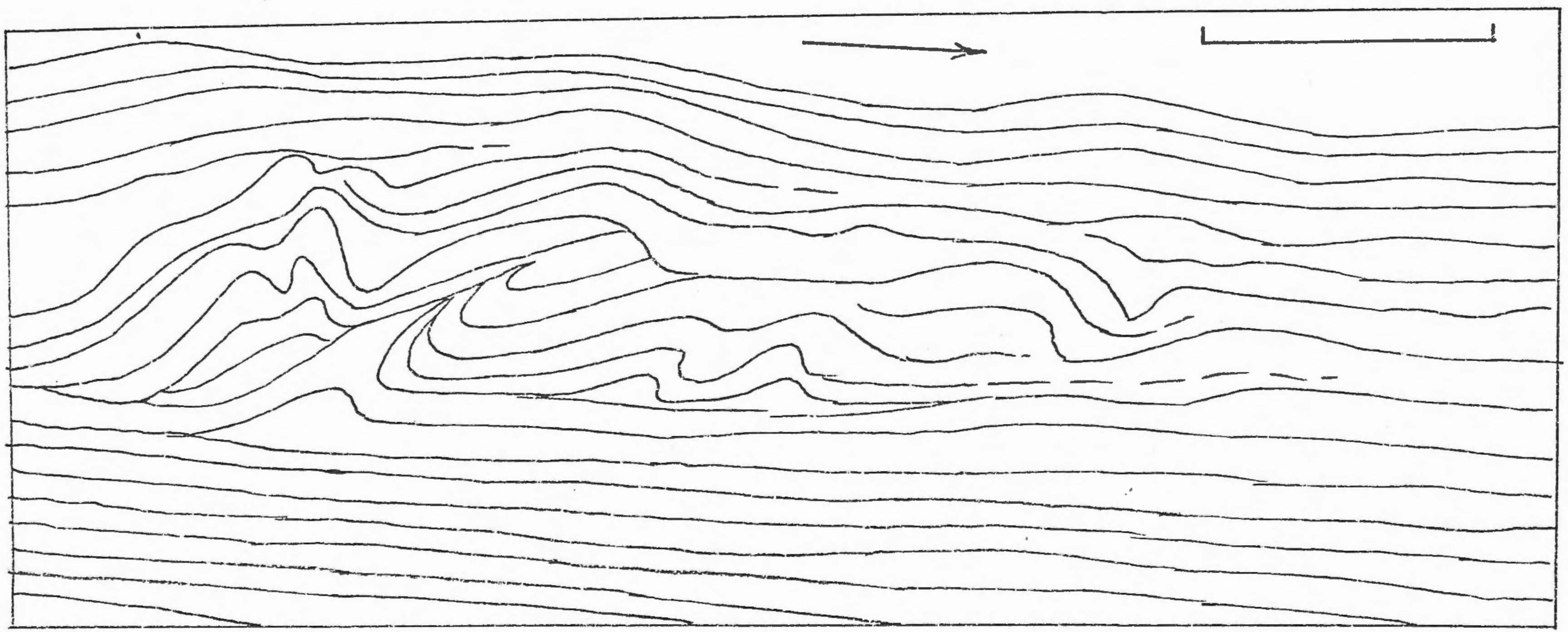


Fig. 43. Convolute bedding in tuffs of the eastern rim of the tuff ring around Big Hole. The direction of movement was downslope, to the right of the sketch (indicated by the arrow). Field sketch. Scale at the top is 4.5 meters long.

synclines lean in the direction of the sliding. The acute angle formed by the axial plane with underlying, undeformed beds is on the downslope side of the folds.

The deformation of the ash beds may have been caused by slumping of incompetent beds with a high pore water content. Sharp separation of most of the convolute beds from underlying, undeformed beds also indicates that the deformation was due to sliding rather than overloading. It is possible that the sliding was initiated by drag at the steam and debris cloud - ash bed interface as a base surge cloud moved across the surface. No current structures characteristic of base surge clouds were noted in the ash beds overlying convolute beds to prove or disprove this theory. It is more likely that most of the convolute bedding was caused by slumping of incompetent ash beds, triggered by seismic activity associated with the eruptions.

Bedding Plane Sags

The deformation of tuff beds by the impact of blocks ejected from the crater is common to all of the tuff rings in the Fort Rock - Christmas Lake Valley basin. The bedding plane sags, or secondary craters, range from 5 cm to several m in diameter. The tuff beds are generally bent downward plastically* under the impacted block (fig. 44a).

*The change in the shape of a solid that does not involve failure by rupture (*Amer. Geol. Inst. Glossary* - 1950).

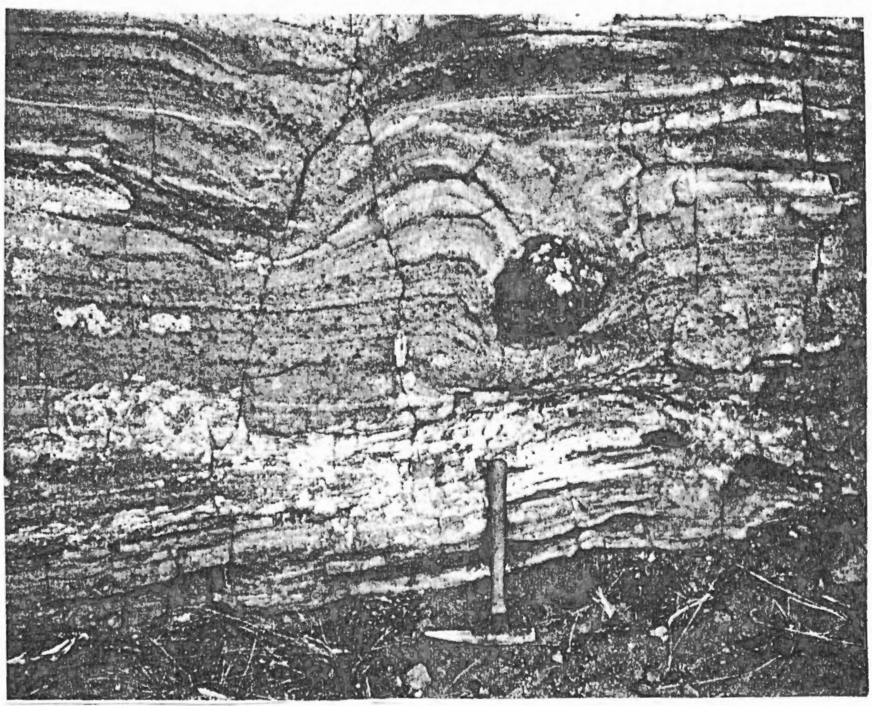


Fig. 44-a. Plastic deformation of lapilli-tuff beds by a block thrown from the vent. Typical of bedding plane sags described in the text, this example is from the tuff ring near Boatwright Ranch. The best example, with block in place, is near the center of the photograph. Another sag is visible on the left, with the block weathered out.

Most of the blocks impacted at an angle, forming asymmetrical secondary impact craters. In places where tuff beds are more competent, impacting blocks deformed them by fracturing and microfaulting as well as by plastic deformation (fig. 44-b and c). At Big Hole, where a 2 m long block impacted into the tuff beds, the bedding was broken and turned back onto itself around the secondary crater rim (fig. 45). This was the only example of overturned bedding in a secondary crater (bedding plane sag) seen in all of the tuff rings studied.

Compaction of the bedding by the impact of blocks was probably due, in part, to the squeezing of interstitial water out of the beds. The unconsolidated ash may be similar to sandy clays or silty clays when considering the mechanical properties. In unconsolidated clays or sandy clays, plasticity is mostly dependant on the percentage of water between grains. Sandy clays will flow if the water content is above 23.3 per cent but are no longer plastic if the water content is below 14.1 per cent (DeSitter, 1964, p. 35). The critical water content of between 14.1 per cent and 23.3 per cent for plastic deformation is possible for an ash bed deposited above water level by a mixture of steam, ejecta, and water. If the water content of the ash beds were below 14 per cent, it is possible that deformation by shearing would occur. The bedding

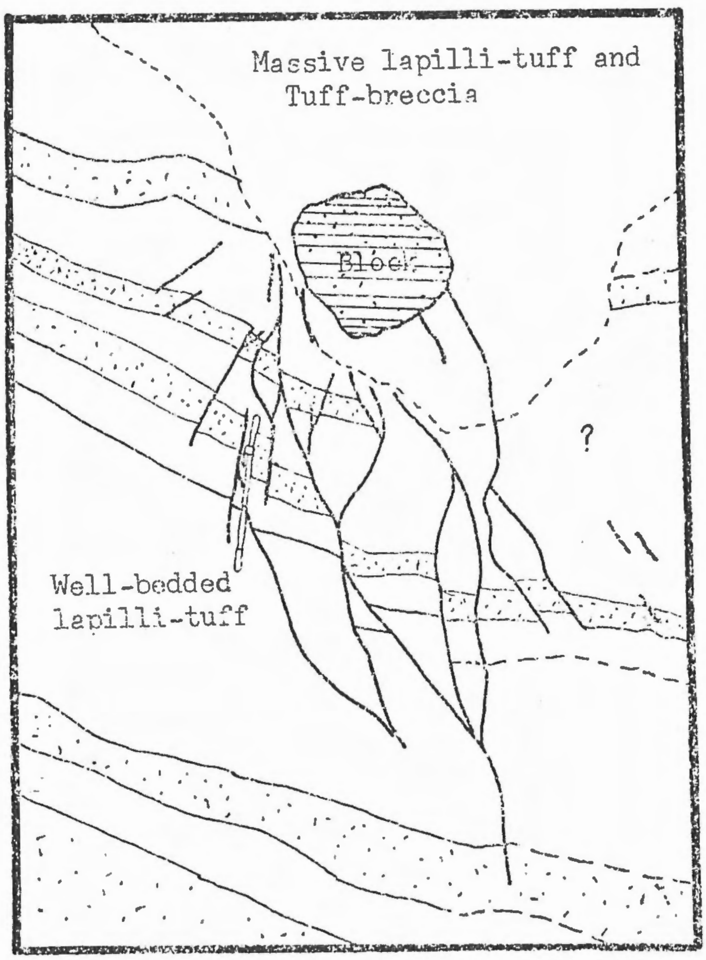


Fig. 44-b. Sketch of fig. 44-c.

Fig. 44-c. Bedding plane sag in lapilli-tuff beds of the tuff ring at Boatwright Ranch. Most of the deformation is by micro-faulting rather than by plastic deformation. The sketch on the opposite page shows the fracture pattern developed below the block as it impacted. The pen in the photograph is 15 cm long.

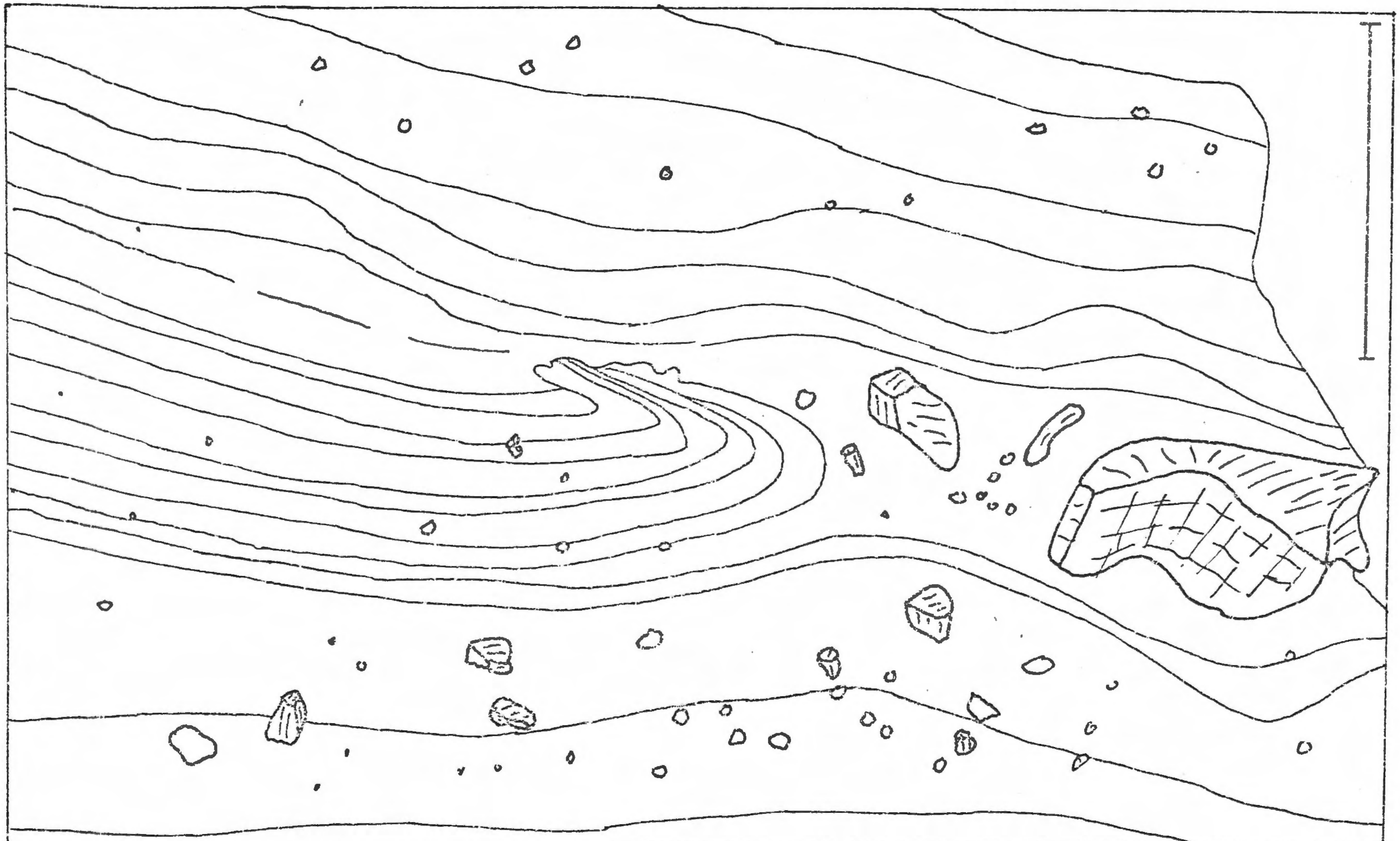


Fig. 45. Secondary Crater, with tuff beds thrown back around a large block (located at the right edge of the sketch). In bedded tuffs and lapilli-tuffs of Big Hole. Field sketch. Scale is 2 m long.

plane sags appear to be good indicators of the plastic, cohesive nature of the freshly deposited ash.

THE SHAPE AND STRUCTURE OF TUFF RINGS WITHIN THE FORT ROCK - CHRISTMAS LAKE VALLEY BASIN

Cross sections of the surface expressions of reconstructed tuff rings, cinder cones and a tuff cone are compared in figure 46. Height-width ratios are for purposes of comparison only and are not the same as the ratios used by Baldwin (1963), whose data are from craters formed by single explosions with a ring of debris excavated from the crater. Cinder cones, located beyond the edge of the former lake, have the lowest height-width ratios of 1:5. Tuff rings located in and near the basin have ratios of 1:10 to 1:30. The ratios of rings built partly underwater and those that are entirely subaerial are similar.

Tuff rings 1 and 2 within the Table Rock tuff ring complex, with height-width ratios of greater than 1:22, formed in the lake. Most of the explosive steam generation during the eruptions probably took place near the surface, when rising magma came into contact with lake water (in addition to ground water encountered at greater depths). The Table Rock tuff cone, with a height-width ratio of 1:9, formed above the surface of the lake, on the rim of Tuff Ring 2. The primary source of water in contact with the magma in the vent appears to have been a highly

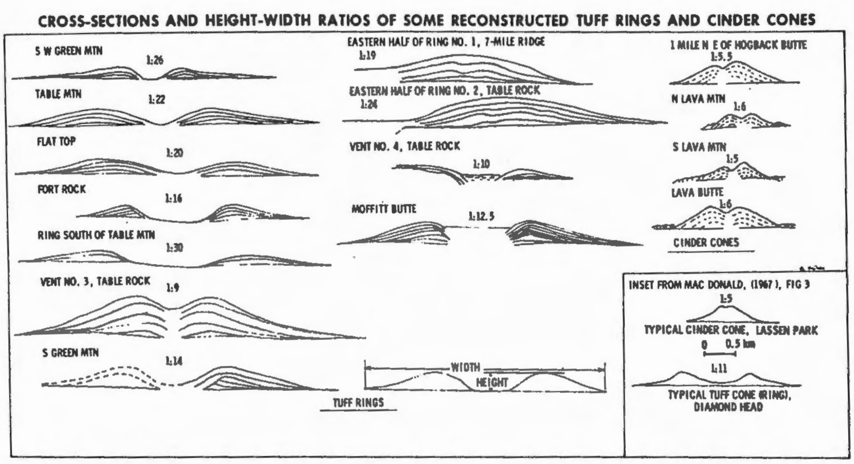


Fig. 46. Cross-sections of the surface expressions of reconstructed tuff rings, a tuff cone, and cinder cones.

permeable aquifer 210 meters below the base of the tuff ring complex (as interpreted from water-well data [appendix 1], the aquifer consists of an open network of fractured lava flows). The sediments between the aquifer and base of the tuff ring complex are nearly impermeable diatomites.

At the Table Rock tuff ring complex, the shapes of tuff rings appear to have been partly dependent on the depth of explosive steam generation which took place when rising magma came into contact with ground or surface water (phreatomagmatic eruptions). After deep explosions, the shape and direction of eruption clouds containing ejecta appear to have been guided by the conduit. Preponderant trajectories of ejecta must have been nearly vertical, falling back near the vent to form a cone with a low height-width ratio similar to that of the Table Rock tuff cone. Shallow explosions at or near the surface probably resulted in a wider spread of ejecta and steam, resulting in tuff rings with height-width ratios of greater than 1:20.

CONCLUSIONS AND SUMMARY

1. The tuff rings in the Fort Rock - Christmas Lake Valley basin of south-central Oregon were formed in and close to a lake during Pliocene-Pleistocene time. Eruptions of the same magma type beyond the edges of the basin produced numerous cinder cones and associated lava flows (with the exception of Hole-in-the-Ground, Moffitt Butte, and Big Hole, which appear to have formed along buried old drainages.

2. The tuff rings were formed by phreatomagmatic eruptions; that is, when rising magma of basaltic composition was chilled on contact with ground or surface water to generate the steam necessary for the eruption. Blocky sideromelane fragments, which are the primary constituent of the ejecta, were formed by the contraction and shattering of the glass after the quenching. Phreatomagmatic eruptions (which are violent relative to basaltic eruptions that are driven by gases from the magma only), consist of rapidly expanding steam clouds laden with ejecta.

3. The amount of steam generated and the depth at which the steam was generated apparently control the height-width ratios of the tuff rings.

4. Ash from these eruptions was deposited by air fall and by base-surge clouds moving across the ground or water surface.

5. The ash was wet and sticky, as seen by ash beds plastered onto steep surfaces, the formation of accretionary lapilli, and plastic deformation of ash beds by blocks flung from the vent.

COMPARISON OF TUFF RINGS, TUFF CONES, AND CINDER CONES

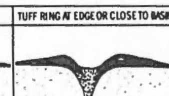
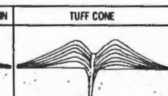
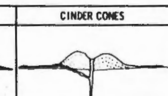
	TUFF RINGS WITHIN THE BASIN	TUFF RING AT EDGE OR CLOSE TO BASIN	TUFF CONE	CINDER CONES
SHAPE AND GEOLOGIC CROSS-SECTION				
HEIGHT-WIDTH RATIO	1:10 - 1:30 (?)	1:10 - 1:30	1:9 - 1:11	1:5 - 1:6
LITHOLOGY	MOSTLY SIDEROMELANE TUFF AND LAPILLI-TUFF, WITH SUBSTANTIAL AMOUNTS OF TUFF-BRECCIA (CONTAINING BLOCKS OF BASALT AND LAKE SEDIMENT). ABUNDANT ACCRETIONARY LAPILLI	SIDEROMELANE TUFF, LAPILLI-TUFF AND TUFF-BRECCIA. POSSIBLY SOME CINDERS AND BASALT FLOWS ASALATE CRATER FILLINGS. ABUNDANT ACCRETIONARY LAPILLI	SIDEROMELANE TUFF, TUFF-BRECCIA AND TUFF-BRECCIA. POSSIBLY A FEW CINDERS AND BASALT FLOWS IN A CRATER LAKE AT THE SUMMIT ABUNDANT ACCRETIONARY LAPILLI	TACHYLITE CINDERS, FLOWS OF HOLOCRYSTALLINE BASALT. TRACES OF SIDEROMELANE PUMICE (LESS THAN 1 PERCENT)
BEDDING	THICK, MASSIVE BEDDING NEAR BASE OF RING (BELOW FORMER WATER LEVEL). THIN, WELL-DEFINED BEDDING ABOVE THE FORMER LAKE LEVEL	WELL-DEFINED, RELATIVELY THIN BEDS FROM BASE TO TOP OF RING	WELL-DEFINED, RELATIVELY THIN BEDS FROM BASE TO TOP (?)	POORLY DEFINED, THICK BEDS
SEDIMENTARY STRUCTURES	MUDSTONE DIKES AT BASE OF RING. ABOVE FORMER LAKE LEVEL THERE ARE, RADIALLY ORIENTED AROUND THE CRATER, DUNES, RIPPLE MARKS TABULAR FORESET BEDDING. ALSO GRADED BEDDING, BEDDING PLANE SAGS. DEFORMATION OF UNDERLYING SEDIMENT	GRADED BEDDING, DUNES, RIPPLE MARKS, TABULAR FORESET BEDDING, BEDDING PLANE SAGS, CONVOLUTE BEDDING	GRADED BEDDING, BEDDING PLANE SAGS. OTHER STRUCTURES NOT SEEN; PROBABLY DUE TO POOR EXPOSURES IN THE TUFF CONES	SOME CRUDE GRADED BEDDING
SOURCE OF WATER FOR GENERATION OF STEAM	WATER FROM THE LAKE AND POSSIBLE DEEP AQUIFER	SHALLOW AQUIFER	DEEP AQUIFER	NONE-MAGMATIC
MECHANISMS OF DEPOSITION OF THE EJECTA	SUBAQUEOUS DEBRIS FLOW, AIR-FALL, BASE SURGE CLOUDS. SLUMPING, REWORKING BY WAVES.	AIR-FALL AND BASE SURGE CLOUDS	AIR-FALL AND BASE SURGE (?)	AIR-FALL, SLUMPING

Fig. 47. Summary, outlining the characteristics of tuff rings, tuff cones, and cinder cones from the Fort Rock - Christmas Lake Valley Basin.

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APPENDIX 1

Measured sections and well logs from the Fort Rock-Christmas Lake Valley Basin and an isopach map based on these logs.

Well 28/15 - 1401

(A. E. Albertson, Alt. 4,315 ft. Drilled by Frank Skillings, 1957. Depth 646 feet.

Materials	Thickness (feet)	Depth (feet)
Sand and clay	18	18
Sand, loose	6	24
Sand and clay	52	76
Shale (tuff)	13	89
Sand and clay	129	218
Sand, fine	114	312
Shale (tuff)	28	340
Clay (diatomite)	273	613
Basalt, black	14	627
Cinders, red	7	634
Rock, lava	8	642
Rock, gray	4	646

Driller's log (well #18 on isopach map). Page B27 of Hampton (1964).

Well 27/15 - 11R2 (well #8)

(Jess Miles, Alt. 4,350 ft. Drilled by Edwin Eskalin, 1947. Depth 90.5 ft.)

Materials	Thickness (feet)	Depth (feet)
Soil, sandy	2.5	2.5
Gravel, sandy	6	8.5
Lava, red, porous	38	46.5
Cinders, red, and black gravel	25.5	72
Ash, white, "packed"	.5	72.5
Cinders, red	3	75.5
Gravel, cemented	.5	76
Gravel, coarse, rounded and sand	2	78
Cinders, red	6	84
Lava, porous, red	3	87
Cinders, red, and gravel	2	89
Gravel, coarse, loose	1.5	90.5

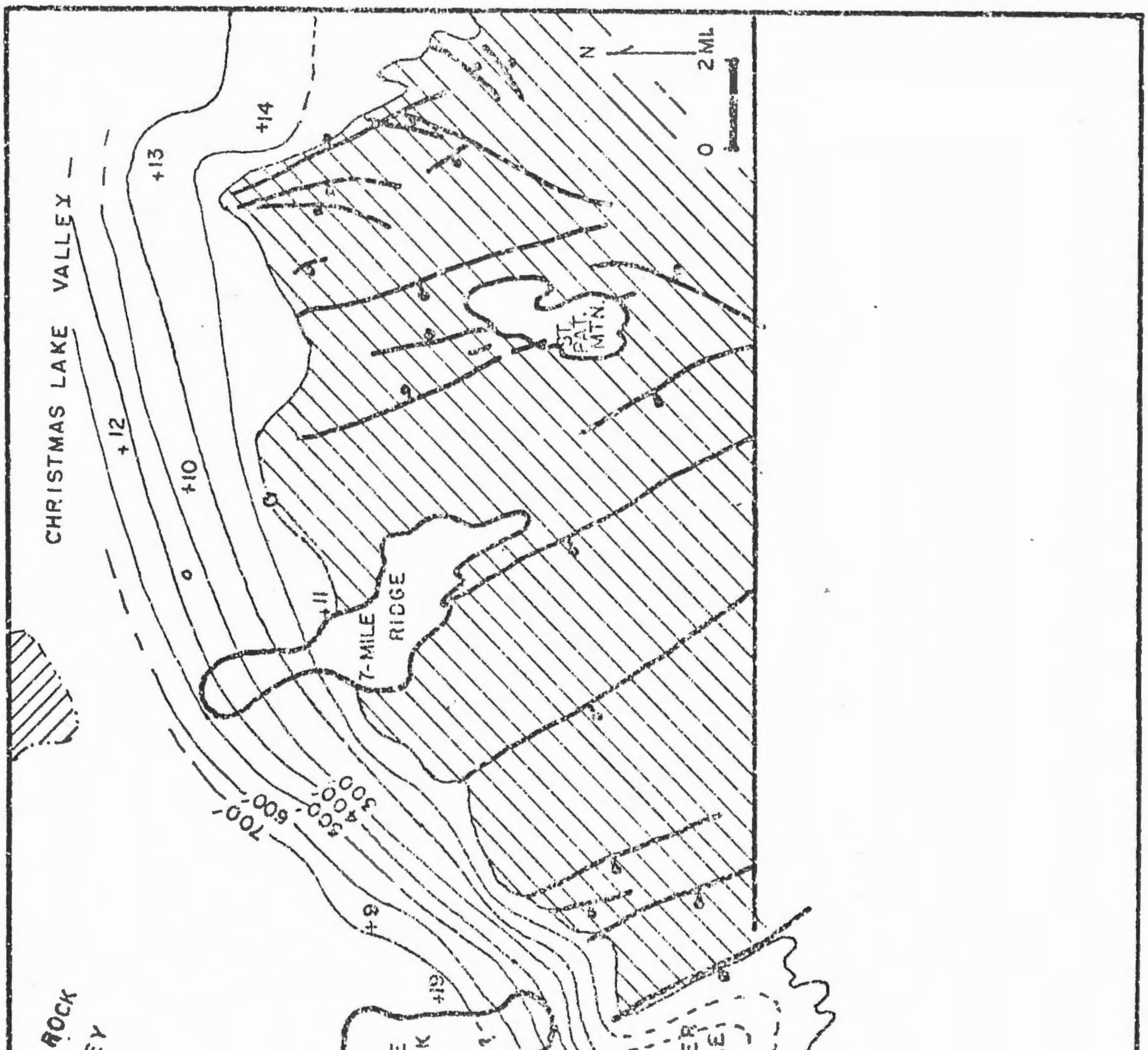
Driller's log from well drilled less than 1000 feet from the edge of Hayes Butte (Hampton, 1964, p. B25). Illustrates coarser nature of sediments and interbedded flows close to the Hayes Butte-Connelly Hills Ridge.

Well 27/16 - 34L1 (well #9)

(Mallett estate, Alt. 4,330 ft. Drilled by Floyd Nicholson, 1957. Depth 828 ft.)

Materials	Thickness (feet)	Depth (feet
Soil	6	6
"Hardpan"	2	8
Diatomaceous earth	282	290
Sand, gray	12	302
Diatomaceous earth	373	675
Basalt, broken	43	718
Basalt, hard, gray	46	764
Basalt, gray, and pumice	5	769
Basalt, broken, black	22	791
Basalt, hard	23	814
Basalt, broken	6	820
Basalt, hard	8	828

Driller's log from well drilled two miles east of Table Rock, illustrating the dominance of fine-grained sediments in the center of the basin. (From Hampton, 1964, p. B25)

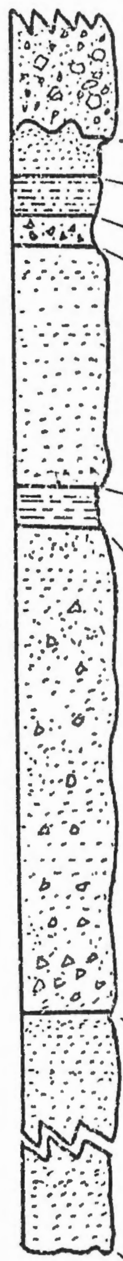

CHRISTMAS LAKE VALLEY
FORT ROCK VALLEY
CONNLEY HILLS
PAULINA MARSH
TABLE ROCK
SILVER LAKE
7-MILE RIDGE
ST. PAT. MTN.
N
0
2 ML
700
600
500
400
300
200
100
+4
+8
+9
+10
+11
+12
+13
+14
+15°
+16
+17
+18
+19

Isopach map of the lake sediments in part of the Fort Rock - Christmas Lake Valley Basin. The zero isopach line (narrow, solid line) is nearly coincident with a wave-cut terrace at an elevation of 4400 feet (1338 meters). Lines of alternate dashes and dots outline volcanic rocks contemporary with or younger than the lake sediments. Heavy solid lines outline tuff ring complexes. Lines slanted to the left represent outcrops of older plateau basalts.

The Connley Hills volcanic complex appears to have been an island throughout the history of the basin, erupting along the fault trending northwest from the east wall of the Silver Lake graben.

WELL #	THICKNESS	
	METERS	FEET
7	not known	
8	27.3	90
9	205	675
10	35.2	116
11	18.2	60
12	129.2	425
13	48.3	158

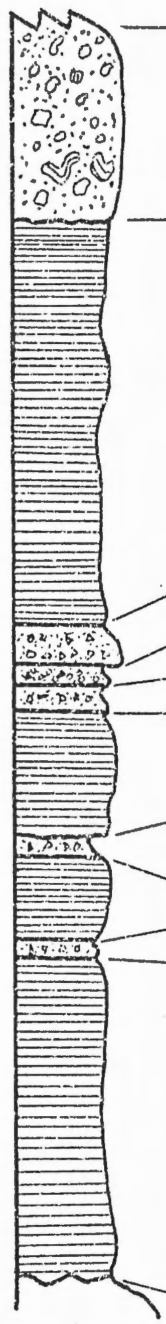
WELL #	THICKNESS	
	METERS	FEET
14	54.4	178
15	73	240
16	7.3	24
17	141	462
18	186.5	613
19	218	718



THICKNESS (METERS)	DESCRIPTION
6+	Massive tuff-breccia, with blocks of the underlying units.
.15	Gray pumice-bearing sandstone; volcanic litharenite. Well-bedded.
.15	White diatomaceous mudstone; thin bedded.
.09	Gray pumice lapilli-tuff.
.9	Well-bedded, submature coarse sandstone; tuffaceous volcanic litharenite. The sandstone contains abundant reworked pumice fragments.
.09	White, well-bedded sandy claystone; possibly diatomaceous.
1.8	Poorly bedded submature medium to coarse pumice-bearing lithic subarkose. Pumice content increases near the base to about 60% of the rock.
4.5+	Well-bedded gray or white medium sandstone; sub-lithite-arenite. Interbedded with the sandstone are a few thin layers of conglomerate, made up of well-rounded pumice fragments. There is some cross-bedding.

Talus covers the base of the section.

Section of sediments exposed under the northwest corner of tuff ring 2; Table Rock tuff ring complex (see plate 1).



THICKNESS (FEET)	DESCRIPTION
15'+	Massive tuff-breccia; Lapilli-tuff at base grades up into breccia with up to 50% bombs and blocks (blocks of lake sediment and basalt.
10'	Finely laminated, white diatomite.
1'	Well-cemented gray lapilli-tuff (graded).
0.5'	Reverse-graded pumice lapilli tuff.
0.5'	Pumice-bearing gray ash.
3'	Finely laminated, white diatomite.
0.5'	Well-sorted white tuff. Base of the bed is stained with limonite.
2'	White diatomite.
0.4'	White, graded lapilli-tuff.
8'	Massive white diatomite.
	Talus covers the base of the section.

Measured section of sedimentary rocks and tuff exposed below the middle tuff ring at Seven-Mile Ridge.

APPENDIX 2

Modal analyses of lavas from the Fort Rock - Christmas Lake Valley Basin.

Modal analyses of basalts from dikes and lava lakes associated with tuff rings:

No.	1	2	3	4	5	6	7	8
Plagioclase phenocrysts	42.5	44.7	18.0	8.0	2.8	8.6	9.3	9.6
Olivine phenocrysts	7.5	16.3	3.7	3.0	Tr.	3.7	Tr.	2.2
Clinopyroxene	-	-	-	22.5	-	-	-	-
Orthopyroxene	-	-	-	-	-	-	-	-
Opaque minerals	1.0	-	-	-	4.7	0.4	5.6	-
Groundmass*	49.0	39.0	-	-	92.3	87.0	85.0	-
Olivine	-	-	23.0	9.0	-	-	-	30.4
Feldspar	-	-	44.1	48.5	-	-	-	35.7
Opaques	-	-	11.0	9.0	-	-	-	19.2
Glass	-	-	-	-	-	-	-	0.5

*See descriptions for groundmass composition if not counted.

No.	9	10	11	12	13	14	15
Plagioclase phenocrysts	57.4	10.1	3.0	24.0	44.0	67.5	60.5
Olivine phenocrysts	12.9	0.3	3.0	5.5	6.0	15.0	13.0
Clinopyroxene	19.7	-	-	-	-	12.0	16.0
Orthopyroxene	-	-	2.0	-	1.5	-	-
Opaque minerals	9.9	6.7	-	-	Tr.	5.5	2.0
Groundmass	-	83.0	92.0	70.5	48.5	-	8.5

Explanation of numbers for Appendix 1

Descriptions of samples from dikes, lava lakes, and flows associated with tuff rings:

1. Horning Bend. Sample from the dike in the center of dome. Black, aphanitic basalt. Diktytaxitic texture. Unoriented phenocrysts of plagioclase (An_{65}) and olivine (altered to iddingsite) in a tachylitic groundmass. The feldspars are zoned, with rims slightly more calcic than the cores.

2. Flat Top. Lava Lake. Dark gray, aphanitic rock with a well-preserved pahohoe surface texture. Hyalocrystalline texture, with 0.5 mm long phenocrysts and clots of zoned feldspars (avg. composition of An_{60}), and olivine in a tachylite groundmass.

3. Moffitt Butte. Lava lake in a parasite cone on the southwest side. Holocrystalline, microporphyritic texture. Phenocrysts of plagioclase (An_{55}) and olivine (altered to iddingsite) in a groundmass of feldspar, olivine and opaque minerals.

4. Southwest Green Mountain. Lava Lake. Black, aphanitic basalt. Subophitic texture, with phenocrysts of olivine and plagioclase (An_{55}) in a groundmass of feldspar, olivine and clinopyroxene.

5. South end of Table Mountain. Lava lake. Platy, gray basalt. A few feldspar (about An_{55}) and olivine phenocrysts in a tachylite groundmass. Groundmass feldspars are altered and stained with hematite.

6. Dike in the center of tuff ring 2, Table Rock complex. Black, aphanitic basalt. Plagioclase (An_{55}) and olivine phenocrysts and clots in fine-grained groundmass consisting of opaque minerals, olivine, and small feldspar laths.

7. Table Rock complex; lava lake in the Table Rock tuff cone. Gray, aphanitic basalt. Phenocrysts of feldspar (An_{65}) and olivine (altered to iddingsite) in a groundmass of feldspar laths, opaque minerals, and olivine. Many of the phenocrysts are in clots of 4 or 5.

8. Table Rock Complex; vertical dike on the north flank of the Table Rock tuff cone. Gray, aphanitic basalt. Zoned plagioclase (avg. composition of An_{60}) and olivine

phenocrysts and clots of phenocrysts in a groundmass of plagioclase laths, olivine, and opaque minerals.

9. Seven-Mile Ridge; dike in the largest ring, located in the center of the ridge. Subophitic texture, with phenocrysts of olivine and feldspar (An_{55}) and groundmass olivine, feldspar and opaque minerals enclosed in ophitic crystals of a clinopyroxene (augite).

10. Saint Patrick Mountain; lava lake in the top of the tuff cone. Black, aphanitic basalt. Diktytaxitic texture. Phenocrysts of altered feldspar (composition of An_{55}) and olivine in a groundmass of feldspar laths and opaque minerals (all the ferromagnesian groundmass minerals have been replaced by opaques).

11. Flow from large cinder cone directly east of Hogback Butte. Dark gray, aphanitic basalt. Small phenocrysts of plagioclase (An_{65}), olivine, and opaque minerals in a groundmass of feldspar, hypersthene, and opaque minerals.

12. Flow from Lava Mountain, a cluster of recent cinder cones. Dark gray aa basalt. Phenocrysts and clots of feldspar (An_{55}) and olivine in a tachylite groundmass.

13. Devil's Garden flow (recent). Dark gray pahoehoe. Hyalocrystalline texture. Large feldspar (An_{65}), olivine, and orthopyroxene phenocrysts in a tachylite groundmass.

14. Basalt of Pliocene age from Picture Rock Pass (flows). Light gray, diktytaxitic basalt. Well-oriented feldspar crystals (composition of An_{63}) enclose small anhedral crystals of olivine and opaque minerals. The olivine is altered to iddingsite.

15. Block from the southernmost tuff ring, Seven-Mile Ridge. Black, angular basalt block. It has an ophitic texture, with feldspar laths and olivine crystals enclosed in 4 to 8 mm long augite crystals. The interstices are filled with a gold-brown, fibrous alteration product.

Modal analyses of tuffs from the Fort Rock - Christmas Lake Valley Basin

No.	1	2	3	4	5	6	7	8	9	10	11
Sideromelane fragments											
Vesicular	18.4	30.3	39.5	72.6	29.5	37.7	16.8	16.7	22.5	34.0	15.4
Nonvesicular	18.4	20.8	13.0	-	8.0	2.4	9.3	13.0	13.5	20.0	28.3
Fine-grained matrix	61.7	35.6	41.5	16.4	57.5	55.3	62.0	70.0	49.0	39.5	47.7
Tachylite fragments	-	-	4.0	-	0.5	-	-	-	9.0	3.0	3.8
Feldspar phenocrysts	1.4	Tr.	Tr.	-	Tr.	2.0	2.5	-	1.5	2.0	0.5
Olivine phenocrysts	Tr.	-	0.5	-	Tr.	0.8	Tr.	-	0.5	0.5	0.2
Pyroxene phenocrysts	-	-	-	-	-	-	-	-	-	-	-
Xenoliths											
Sedimentary	-	2.9	-	-	-	1.8	1.9	-	0.5	1.0	-
Volcanic	Tr.	-	-	4.7	4.0	-	-	-	2.5	-	3.8
Opaque minerals	-	-	-	6.4	-	-	7.2	-	-	-	-
Calcite cement	-	9.2	1.5	-	0.5	-	-	Tr.	1.0	-	-
Zeolite cement	-	-	-	-	-	-	-	-	-	-	-

Modal analyses of tuffs (continued)

No.	12	13	14	15	16	17	18	19	20	21	22
Sideromelane fragments											
Vesicular	16.5	21.0	70.8	7.0	33.1	37.0	44.0	22.0	24.5	24.7	2.4
Nonvesicular	20.0	14.0	3.6	32.4	15.5	6.5	14.0	17.0	11.7	11.7	20.8
Fine-grained matrix	30.0	42.5	24.9	35.1	34.6	46.0	39.5	56.0	58.2	58.2	31.4
Tachylite fragments	12.5	18.0	0.2	0.1	3.0	2.0	0.5	2.0	3.9	3.9	10.5
Feldspar phenocrysts	4.0	1.0	0.2	0.8	2.6	5.0	1.0	0.5	1.0	1.0	12.8
Olivine phenocrysts	0.5	Tr.	0.4	-	0.6	1.5	1.0	Tr.	0.6	0.6	3.5
Pyroxene phenocrysts	-	-	-	-	-	1.0	-	-	-	-	0.6
Xenoliths											
Sedimentary	-	-	-	19.6	-	-	-	-	-	-	-
Volcanic	2.5	-	-	2.2	0.4	-	-	1.5	-	-	18.0
Opaque minerals	-	-	-	0.1	1.0	-	-	-	-	-	-
Calcite cement	14.0	-	-	-	9.2	1.0	-	1.0	-	-	-
Zeolite cement	-	-	-	-	-	-	-	-	-	-	-

Modal analyses of tuffs (continued)

No.	23	24	25	26	27	28	29	30	31	32	33
Sideromelane fragments											
Vesicular	43.4	20.0	41.6	26.0	2.4	3.2	22.5	24.5	27.0	19.4	24.3
Nonvesicular	22.0	19.5	8.6	16.0	23.3	32.9	22.5	7.0	9.0	12.2	18.4
Fine-grained matrix	23.6	47.5	32.3	41.0	63.1	58.5	40.0	37.0	50.0	54.4	49.8
Tachylite fragments	4.9	3.0	3.3	4.0	-	-	3.5	22.5	3.0	-	-
Feldspar phenocrysts	2.0	4.5	4.0	Tr.	2.8	Tr.	1.0	5.0	9.0	4.6	2.4
Olivine phenocrysts	4.0	4.0	0.6	0.5	0.4	Tr.	1.0	3.0	0.5	7.2	2.0
Pyroxene phenocrysts	-	-	-	-	-	-	-	-	-	-	-
Xenoliths											
Sedimentary	-	-	-	8.5	-	-	-	-	-	-	-
Volcanic	-	1.5	-	4.0	1.0	-	6.5	1.0	1.5	2.1	-
Opaque minerals	-	-	-	-	6.8	5.4	-	-	-	-	-
Calcite cement	-	-	-	-	0.8	-	-	-	-	-	1.0
Zeolite cement	-	-	9.6	-	-	-	-	-	-	-	2.1

Modal analyses of tuffs (continued)

No.	34	35	36	37	38	39	40	41	42	43	44
Sideromelane fragments											
Vesicular	31.3	46.5	38.0	15.5	16.8	36.5	18.5	5.5	34.5	29.7	36.6
Nonvesicular	35.2	14.0	3.0	16.5	24.4	5.5	14.5	22.5	20.5	8.0	26.9
Fine-grained matrix	28.5	38.0	51.0	56.5	45.87	33.5	45.5	49.5	40.0	47.8	36.3
Tachylite fragments	-	2.0	-	4.5	-	19.0	15.5	9.0	2.0	2.7	-
Feldspar phenocrysts	3.1	Tr.	3.5	4.5	7.2	3.0	2.0	3.0	1.5	3.3	0.2
Olivine phenocrysts	1.8	0.5	0.5	Tr.	0.2	1.5	2.0	Tr.	1.5	2.5	Tr.
Pyroxene phenocrysts	-	Tr.	-	-	-	-	-	-	-	-	Tr.
Xenoliths											
Sedimentary	-	-	-	-	-	-	-	1.5	-	-	-
Volcanic	-	-	4.0	2.5	3.4	1.0	-	9.0	-	-	-
Opaque minerals	-	-	-	-	-	-	-	-	-	-	-
Calcite cement	-	-	-	-	1.7	-	2.0	-	-	5.9	-
Zeolite cement	-	-	-	-	0.4	-	-	-	-	-	-

Modal analyses of tuffs (continued)

No.	45	46	47	48	49	50	51	52	53	54
Sideromelane fragments										
Vesicular	0	44.3	26.5	6.5	22.8	32.0	24.0	45.0	-	39.0
Nonvesicular	40.9	27.4	20.5	6.4	22.8	17.0	11.9	-	-	-
Fine-grained matrix	55.9	16.41	47.7	65.0	42.7	46.0	55.3	-	-	-
Tachylite fragments	Tr.	Tr.	-	2.0	Tr.	-	-	51.5	96.5	58.5
Feldspar phenocrysts	1.6	0.9	4.4	0.8	10.0	3.0	5.5	2.5	2.5	1.0
Olivine phenocrysts	1.6	3.0	1.0	Tr.	1.6	Tr.	0.6	1.0	1.0	1.5
Pyroxene phenocrysts	-	-	-	-	Tr.	0.5	Tr.	-	-	-
Xenoliths										
Sedimentary	-	-	-	-	-	-	-	-	-	-
Volcanic	-	-	-	19.3	-	-	-	-	-	-
Opaque minerals	-	-	-	-	-	-	-	-	-	-
Calcite cement	-	-	-	-	-	-	-	-	-	-
Zeolite cement	-	8.0	-	-	-	-	2.0	-	-	-

APPENDIX 3

Modal analyses of the tuffs from the Fort Rock - Christmas Lake Valley Basin.

APPENDIX 3 - Explanation of sample numbers

1. Table Rock complex. The southeast edge of ring 1. Gray lapilli-tuff. Sideromelane fragments (vesicular and nonvesicular) and rounded silicic ash fragments in a matrix of brown fine-grained glass particles.

2. Table Rock complex; from the base of ring 2 on the northwest side. Massive orange-brown tuff. Vesicular sideromelane fragments up to 6 mm in diameter and mudstone fragments are in a matrix of fine-grained glass fragments and clay. Each sideromelane fragment is rimmed with palagonite. There are clots of olivine and plagioclase phenocrysts in the glass.

3. Table Rock complex. Top of section, northwest side of ring no. 2. Massive orange tuff-breccia. Vesicular sideromelane fragments in a matrix of very fine-grained glass. There are phenocrysts of plagioclase (An_{50}) and olivine. The rims of sideromelane fragments are altered to palagonite.

4. Table Rock complex. West-central portion of ring no. 2. Orange-brown tuff-breccia. Large (up to 2.5 cm in diameter), vesicular sideromelane fragments with accretionary coatings of fine-grained glass particles in a matrix of glass fragments. The glass fragments are partly altered to palagonite.

5. Table Rock complex. Outer edge, ring 2. Yellow-brown lapilli-tuff. Vesicular and nonvesicular sideromelane fragments, olivine and feldspar crystals, and fragments of aphanitic basalt all have accretionary coats of fine-grained glass particles.

6. Table Rock complex. Upper beds of ring no. 2, west flank. Yellow-brown lapilli-tuff. Poorly sorted, with a bimodal distribution of fragment sizes at 0.75 mm (vesicular and nonvesicular sideromelane) and at about 0.005 mm (fine-grained glass particles and diatomite). There are phenocrysts and clots of olivine and feldspar (An_{60}).

7. Table Rock Complex. Central-west part of ring 2; uppermost beds. Yellow-brown tuff. Nearly identical to the description of 17.

8. Table Rock complex. Central-west part of ring 2; close to the crater. Brittle, yellow-brown tuff. Vesicular and nonvesicular sideromelane fragments in a matrix of fine-grained glass particles and diatomite. The edges of sideromelane fragments are altered to palagonite.

9. Table Rock complex. Northern edge of ring 2. Well-bedded brown lapilli-tuff. Vesicular and nonvesicular sideromelane fragments, tachylite, obsidian and siliceous pumice sand, clay fragments, and plagioclase and olivine crystals are in a matrix of clay and fine-grained basaltic glass. Glass fragments are partly altered to palagonite.

10. Table Rock complex. North end of ring 2. Thinly bedded yellow-brown lapilli-tuff. Graded bedding observed in thin section, from 1.5 mm diameter sideromelane fragments at the top of the bed. There are small phenocrysts of olivine and plagioclase (An_{60}) in the glass.

11. Table Rock complex; high in the section, ring no. 2, east flank. Brown tuff collected from base surge dunes. There are alternating 1 cm thick beds of: 1. poorly cemented 0.5 to 0.2 mm sideromelane fragments with no matrix and 2. 0.1 mm diameter sideromelane fragments in a matrix of very fine-grained glass particles. Some of the fragments are partly altered to palagonite.

12. Table Rock complex; collected from dunes on the east flank of ring no. 2. Very well-bedded brown tuff. Graded beds as thin as 1.5 mm, with sideromelane fragments of 0.5 mm diameter at the base to 0.02 mm diameter at the top. Most of the slightly palagonitized sideromelane fragments are nonvesicular. There is some calcite cement.

13. Table Rock complex. Center of crater; ring no. 2. Brittle yellow-brown tuff. Very poorly sorted vesicular and nonvesicular glass fragments and tachylite in a matrix of dark red-brown fine-grained glass fragments. All the glass is partly altered to palagonite. Vesicles and pore space is filled with a zeolite cement.

14. Table Rock complex. Sample is from the southwest flank of Table Rock tuff cone (no. 3). Brittle gray-brown rock, orange on a weathered surface. Vesicular and non-vesicular sideromelane fragments, basalt and tachylite fragments in a matrix of fine-grained glass fragments. All the glass fragments are partly altered to palagonite.

15. Table Rock complex. The edge of vent 4; base of the section. Massive, yellow-brown lapilli-tuff. Sideromelane fragments, clay fragments and feldspar and olivine crystals in a matrix of clay and fine-grained glass particles.

16. Table Rock complex; from the center of vent 5. Yellow-brown lapilli-tuff. Vesicular sideromelane fragments (up to 8 mm in diameter) in a matrix of fine-grained sideromelane fragments and clay. The sideromelane fragments are partly altered to palagonite.

17. Table Rock complex; ring no. 7, near the base of the ring. Massive orange lapilli-tuff. Very poorly sorted. Partly palagonitized sideromelane fragments in a matrix of orange-brown fine-grained glass particles. There is some calcite cement.

18. Table Rock complex; high in the section, north edge of ring 7. Yellow-brown lapilli-tuff. Trimodal size distribution of particle sizes, consisting of 2 mm diameter vesicular sideromelane, 0.1 mm nonvesicular sideromelane and 0.005 mm diameter fragments which make up the matrix. There are some accretionary coatings on the larger fragments. Larger glass fragments contain phenocrysts of olivine and feldspar (An_{55}).

19. Table Rock complex; from vertical beds in vent no. 8, 3 feet from the crater wall. Yellow-brown lapilli-tuff.

20. Fort Rock. Gray-brown lapilli-tuff. Sideromelane fragments in a matrix of very fine-grained glass fragments, opaque minerals and diatomite. Sideromelane glass is partly altered to palagonite. Phenocrysts and clots of olivine and feldspar (An_{55}) are included in the glass.

21. Fort Rock. Well-bedded yellow-brown lapilli-tuff. Poorly sorted sideromelane fragments in a matrix of fine-grained glass particles and crystals. Many of the glass fragments contain phenocrysts and clots of olivine and feldspar (An_{50}).

22. Hole-in-the-Ground; south wall. Yellow-brown lapilli-tuff, consisting of vesicular sideromelane, basalt and andesite fragments with thin, accretionary coats of fine-grained glass particles. Olivine, plagioclase (An_{45}) and a trace of clinopyroxene occur as phenocrysts in the glass fragments.

23. Big Hole; east rim. Gray, well-bedded lapilli-tuff. There is a bimodal distribution of fragment sizes; most of the sideromelane fragments have a mean diameter of 1.5 and 0.1 mm. Olivine and feldspar (An_{55}) occur as phenocrysts in the glass and as loose crystals.

24. Northeast flank of the tuff ring around Big Hole. Gray-brown lapilli-tuff. These are mostly sideromelane glass particles, with lesser amounts of basalt fragments, plagioclase (An_{55}), olivine, and an orthopyroxene in a matrix of fine-grained glass particles. In the outer 0.5 mm of the block of tuff, the glass is partly altered to palagonite.

25. Moffitt Butte. Bright orange lapilli-tuff. Vesicular palagonite fragments with dark brown accretionary coatings of fine-grained glass fragments, nonvesicular sideromelane, and tachylite fragments are bound together by zeolite cement.

26. South end of Table Mountain. Brown lapilli-tuff. Sideromelane fragments, well-rounded obsidian pebbles and sand, olivine basalt fragments, and claystone fragments in a matrix of fine-grained glass particles and clay.

27. South end of Table Mountain. Orange-brown lapilli-tuff. Vesicular and nonvesicular sideromelane fragments, rounded olivine and feldspar grains, and rounded obsidian sand-sized fragments in a matrix of fine-grained glass particles.

28. North end, Table Mountain. Dark orange-brown lapilli-tuff. Non-vesicular sideromelane glass fragments in a matrix of fine-grained glass particles. The glass fragments are partly altered to palagonite. There are some small patches of calcite cement.

29. Tuff ring south of Table Mountain. Orange-brown lapilli-tuff. Vesicular sideromelane fragments and a few basalt fragments in a matrix of dark brown fine-grained glass particles and small feldspar crystals.

30. North edge, Horning Bend. Gray lapilli-tuff, weathers to an orange color. Fragments of sideromelane glass and basalt fragments in a matrix of fine-grained glass, olivine and feldspar crystals.

31. Horning Bend. Top of tuff sequence, northeast flank. Matrix from a massive, gray tuff-breccia. Sideromelane glass fragments, plagioclase (An_{60}), opaque minerals, and olivine. The sideromelane fragments have thin palagonite rims.

32. Tuff ring on Boatwright Ranch; northeast flank. Well-bedded brown tuff. Accretionary lapilli, sideromelane fragments and some basalt fragments are in a matrix of brown fine-grained glass particles. Olivine and feldspar (An_{65}) occur as phenocrysts in the glass fragments.

33. Tuff ring on the southwestern slope of Green Mountain. Gray-brown tuff. Vesicular sideromelane fragments with accretionary coats of very fine-grained glass particles. Fragments without accretionary coats are partly altered to palagonite. There is some calcite cement. There are subhedral phenocrysts of olivine and plagioclase (An_{55}).

34. Tuff ring on the southern slope of Green Mountain. A well-bedded, light brown lapilli-tuff from the base of the ring. Well-sorted vesicular sideromelane fragments olivine and feldspar (An_{50}) crystals in small-scale cross-beds. Each of the 2 mm thick cross-beds is graded, with glass fragments 1.5 mm in diameter at the base to 0.1 mm in diameter at the top of each bed.

35. Tuff ring on the southern slope of Green Mountain. The sample is from the uppermost 40 feet of tuff in the ring. Well-bedded, orange-brown lapilli-tuff. Vesicular and nonvesicular sideromelane fragments with accretionary coatings of fine-grained glass particles. Olivine, plagioclase (An_{50}) and hypersthene occur as phenocrysts in the glass fragments.

36. Seven-Mile Ridge. Basal tuff-breccia from the middle tuff ring located in the lake basin. Orange-brown, massive tuff. Lapilli of vesicular sideromelane (up to 5 mm in diameter), tachylite, and diatomite fragments in a matrix of fine-grained glass fragments. The glass fragments contain phenocrysts and clots of olivine and plagioclase (An_{60}).

37. Seven-Mile Ridge; middle ring located in the lake basin. From the thin edge of the basal tuff-breccia (1½ miles from the vent). Gray lapilli-tuff. Extremely poorly sorted vesicular and nonvesicular sideromelane fragments in a matrix of diatoms and fine-grained glass fragments. Diatomite and the glass fragments are well-mixed.

38. Seven-Mile Ridge. From the west side of the middle ring in the lake basin. Matrix from a massive dark orange-brown tuff-breccia. There is a tri-modal size distribution of particles; vesicular sideromelane fragments (1 mm diameter), nonvesicular sideromelane (0.1 mm diameter) and the matrix which consists of fine-grained glass fragments (approximately 0.005 mm diameters) and diatomite. There are some tachylite and crystalline basalt fragments.

39. Seven-Mile Ridge. From the southernmost ring. Massive, yellow tuff. Vesicular sideromelane fragments in a matrix of fine-grained glass particles. The sideromelane fragments are partly altered to palagonite.

40. Seven-Mile Ridge; southern end of the ridge, which is located beyond the edge of the lake basin. Orange-brown lapilli-tuff. Nonvesicular sideromelane fragments have accretionary coatings of fine-grained glass fragments.

41. Seven-Mile Ridge; sample is from the base of the largest ring in the center of the complex. A moderately sorted tuff consisting of palagonitized sideromelane fragments, tachylite, mudstone fragments and olivine and feldspar crystals.

42. Seven-Mile Ridge. From the edge of the largest ring, above a buried fault scarp. Orange-brown lapilli-tuff. Similar to sample 37.

43. Flat Top; southeast edge. Orange-brown lapilli-tuff. Vesicular sideromelane fragments with 0.1 mm thick accretionary coats of fine-grained glass particles and nonvesicular sideromelane fragments are in a matrix of orange-brown, fine-grained glass particles. All pore space is filled with calcite cement.

44. Ring E-2, east end of Christmas Lake Valley. Gray lapilli-tuff. Bimodal size distribution of glass fragments, with modes at 1.5 and 0.05 mm. Larger, vesicular glass particles are coated with accretionary layers of fine-grained glass particles. Olivine and feldspar (An_{45}) occurs as small phenocrysts in some of the glass fragments.

45. Ring E-3, east end of Christmas Lake Valley. Orange-brown tuff. Large nonvesicular sideromelane fragments in a matrix of fine-grained glass fragments. All glass fragments are rimmed with palagonite.

46. Ring E-4, east end of Christmas Lake Valley. Brittle orange-yellow tuff. Vesicular and nonvesicular glass fragments are altered to palagonite. Clots and phenocrysts of plagioclase (An_{65}) and olivine in the palagonite are unaltered. All pore space is filled with a zeolite cement.

47. Ring SE-0, southeast edge of Christmas Lake Valley. Brown lapilli-tuff. Nonvesicular sideromelane fragments are in a matrix of very fine-grained glass particles.

48. Ring SE-1, southeast corner of Christmas Lake Valley. Well-bedded gray-brown lapilli-tuff. Vesicular and nonvesicular sideromelane fragments, crystalline basalt fragments, and tachylite in a matrix of very fine-grained glass particles. All fragments over 0.5 mm in diameter have thin accretionary coatings. The glass fragments are partly altered to palagonite.

49. St. Patrick Mountain; northeast edge, near the base. Orange-brown lapilli-tuff. Vesicular sideromelane fragments are in a matrix of fine-grained glass fragments. All glass fragments are partly altered to palagonite.

50. St. Patrick Mountain; east edge, near the base. Massive, yellow-brown tuff. Poorly sorted vesicular and nonvesicular sideromelane fragments in a matrix of fine-grained glass particles. Zoned feldspars (avg. An_{55}) and olivine occur as phenocrysts in the larger glass fragments. Partly altered to palagonite.

51. Fandango Canyon (large tuff ring adjacent to St. Patrick Mountain). South end of the ring. Poorly bedded, yellow-brown lapilli-tuff. Nearly identical to sample 50.

52. Cinder cone along Oregon State Highway 31, 4½ miles south of Horse Ranch. Cinders from the base of the cone, near the center. Black, orange, red and brown scoriaceous cinders, 4 to 6 cm in diameter. Cinders composed of sideromelane are less vesicular (15-25%) than the tachylite cinders (about 40%). The sideromelane cinders are partly altered to palagonite.

53. Cinder cone along Oregon State Highway 31, 4½ miles south of Horse Ranch. Cinders from the outer flank. Black cinders, 4 to 6 cm in diameter. Feldspar phenocrysts in a tachylite groundmass.

54. Cinder cone along Oregon State Highway 31, 4½ miles south of Horse Ranch. Bright red cinders from the vent. Small feldspar and olivine phenocrysts in a tachylite groundmass. The few sideromelane fragments are altered to palagonite.