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ARTICLES ON RECENT VULCANISM IN OREGON

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RECENT VOLCANIC LANDFORMS IN CENTRAL OREGON*

By Norman V. Peterson and Edward A. Groh**

Introduction

As the race to be the first mortals on the moon continues, the questions of how the lunar surface features originated and what rock types they contain are still not answered.

Many of the lunar configurations that are telescopically visible certainly resemble volcanoes and features associated with them. Even if only a part of the moon's surface has been formed by volcanic processes, some of the smaller volcanic forms, such as hummocky lava flow surfaces, spatter cones, and lava tubes could be present. If these features exist, they could provide ready-made shelters to protect men and vehicles from the hostile environment of radiation, high temperatures, and meteorite and dust bombardment.

A reconnaissance of the Bend-Fort Rock area in central Oregon shows that it has a wealth and variety of fresh volcanic landforms that should be of interest to the planners of our lunar programs as well as to the students of volcanology or to those curious about the rocks of Oregon.

Recent Volcanic Activity in Oregon

Before discussing central Oregon specifically, it may be well to look at the pattern of Recent volcanic activity in all of Oregon. "Recent" volcanism is that which occurred during the Recent Epoch of the geologic time scale, beginning at the close of the Pleistocene (glacial) Epoch about 11,000 years ago and extending to the present.

As shown in Figure 1, numerous lava flows, domes, and pumice and cinder cones of Recent age are present throughout the High Cascades and their eastern slopes, extending as a belt from Mount Hood to Crater Lake, with the greatest concentration in the Three Sisters area. This belt of

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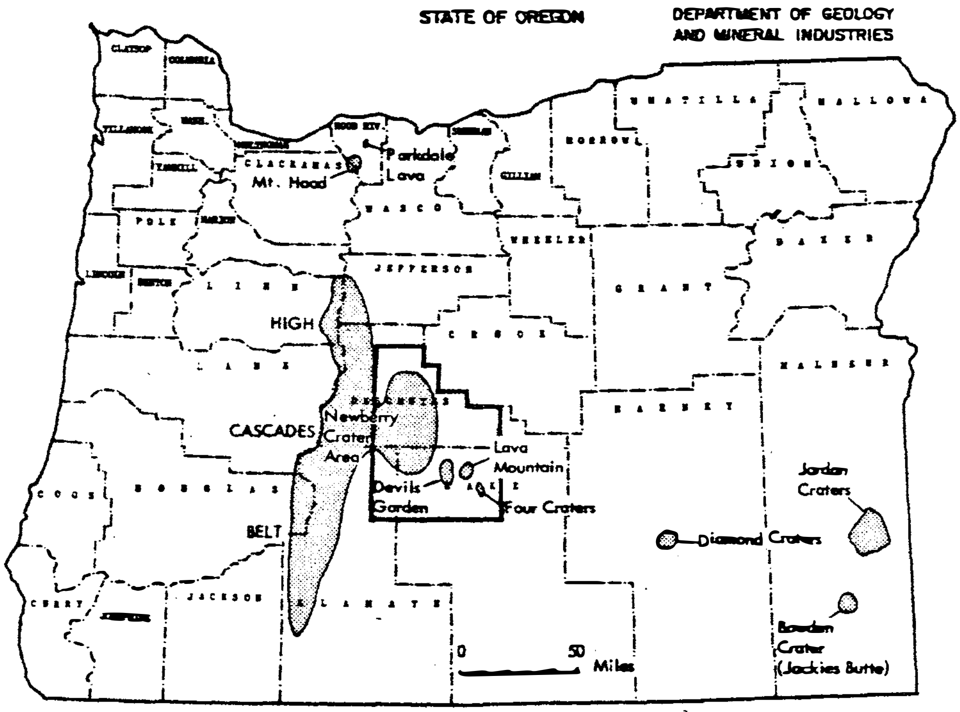

Figure 1. Index map of Oregon showing areas of Recent volcanism.

volcanism contains such well-known features as the Belknap Craters and surrounding lava field, more commonly called the McKenzie Highway lava field; the flow damming Davis Lake; the cones and lava flow damming Clear Lake; cones and flows around the Three Sisters; Lava Butte and its rough lava field; the Lava Cast Forest; and, of course, Crater Lake. A more complete list and description of the numerous Recent volcanic features in this belt, including the Newberry Crater area, can be found in the geologic map by Howel Williams (1957).

Other Recent lava fields and associated cinder cones that are not nearly as well known or described in geologic literature include Devils Garden, Lava Mountain lava field, and Four Craters lava field. These border the north part of the Fort Rock and Christmas Lake Valleys. Jordan Craters, Bowden Crater, and Diamond Craters are isolated Recent eruptive centers located in southeastern Oregon.

The time of eruption of some of Oregon's volcanoes has been determined quite accurately by radiocarbon dating of carbonaceous material. For example, pumice from the cataclysmic eruptions of Mount Mazama fell about 6,600 years ago. Similarly, a pumice eruption from Newberry

Volcano has been dated at about 9,000 years ago and a later one around 2,000 years.

The age of many of the Recent volcanic rocks can be only inferred on the basis of such factors as appearance and geologic relationship. In the estimate of some volcanologists, Lava Butte and the McKenzie Highway lava field are about 1,000 years old. The writers believe the Four Craters cones and lava field to be about this same age. More study and observation of Oregon's Recent lavas may produce carbonaceous materials which will provide accurate determination of their ages by the radiocarbon method.

Another very young eruption gave rise to the Parkdale lava flow, which lies in the valley of the Middle Fork of the Hood River at the base of Mount Hood. It is a block-type flow of probable andesitic composition, about three miles in length. The terminus of the flow is about one mile west of the town of Parkdale and reaches a thickness of more than 100 feet. A thin ash fall around the upper flanks of Mount Hood is believed, from tree-ring dating, to have resulted from a short eruption in the main crater about the year 1800, and may be the last fairly well-substantiated volcanism known in Oregon. Some fumarolic activity still exists on Mount Hood near Crater Rock and at the headwall of Reid Glacier.

In our neighboring state of Washington, report of a short eruption at Mount St. Helens producing an ash fall during November 1843 is well documented. There is evidence that a small, blocky andesite flow may have been extruded on the mountainside around 1838. Also, it has been scientifically demonstrated that an ash eruption may have taken place about 1802. Fumarolic action is still present on this mountain.

To the south in California, Mount Lassen, the United States' latest active volcano, had its most recent eruptions from 1914 to 1917.

Recent Volcanic Areas in Central Oregon

During the summer of 1962, in cooperation with the Bend Chamber of Commerce, a reconnaissance of the area south and east of Bend, including the northern parts of the Fort Rock and Christmas Lake Valleys, was made to determine the extent and variety of Recent volcanic landforms. It is not the intent to list every feature but to show areas where there are concentrations and to illustrate and describe briefly some of the typical landforms.

Figure 2 shows that most of the recent volcanism is within a broad, northwest-trending zone extending from the Three Sisters area at the crest of the High Cascades southeastward through Newberry Volcano and the Devils Garden area until it terminates in the Four Craters lava field in the north part of the Christmas Lake Valley.

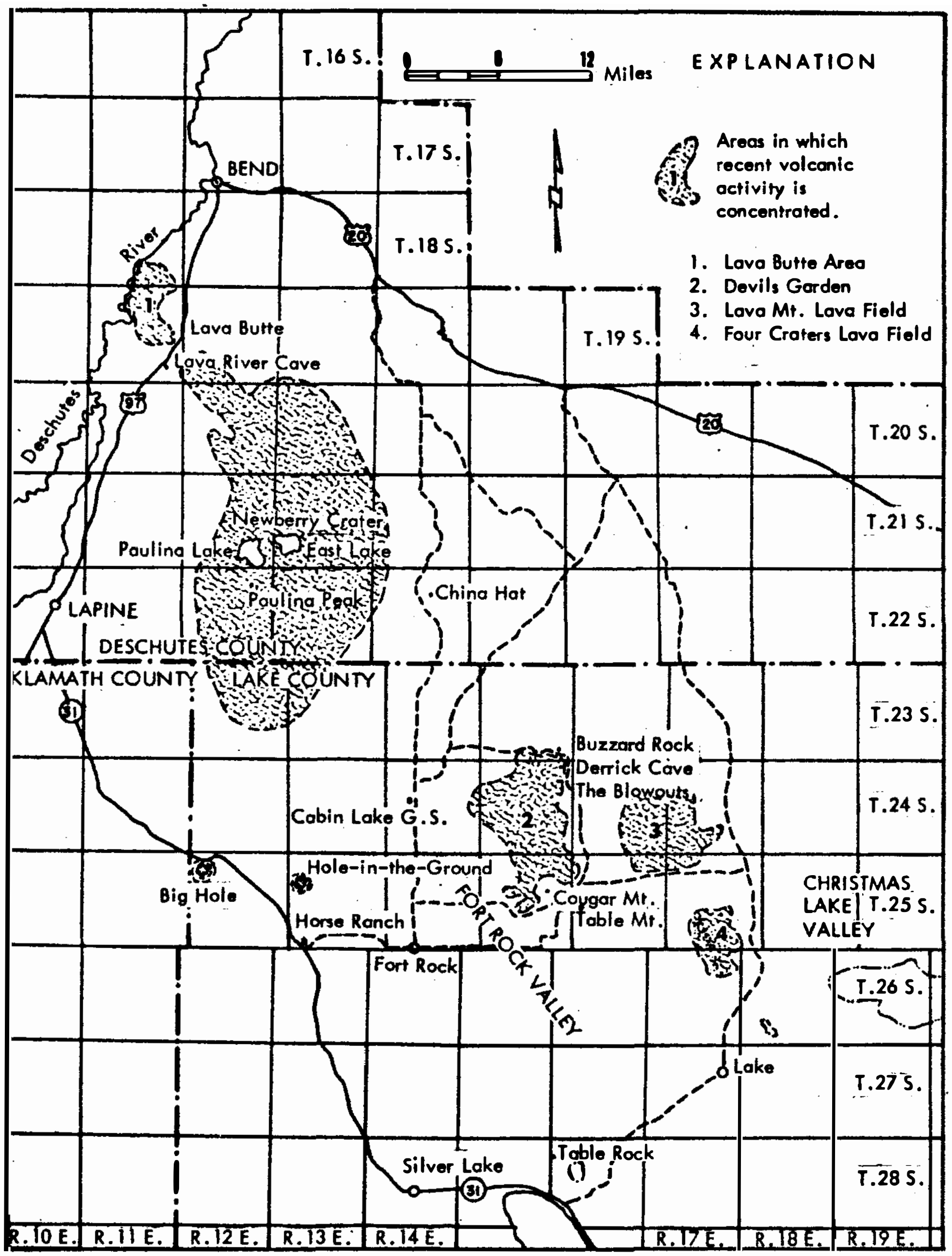

Figure 2. Index map showing areas of Recent volcanic landforms in central Oregon.

Four Craters lava field

This unnamed area, for this report called the Four Craters lava field, is the most remote and farthest southeast area of very recent lava flows and cinder cones. It covers about 12 square miles in Ts. 25 and 26 S., R. 17 E. on the northern edge of the Christmas Lake Valley. This relatively small area is a typical example of the alignment of cinder cones on a strong fissure from which basaltic lavas have been erupted. The four main cratered cinder cones with smaller parasitic scoria mounds are surrounded by clinkery aa flow lavas that came from numerous vents along a fissure that trends about N. 30° W.

Lava Mountain lava field

A large basalt shield-type cone lies to the east of the Devils Garden lava field and is called Lava Mountain. This broad, shallow cone covers an area 6 to 7 miles in diameter mainly in T. 24 S., Rs. 16 and 17 E. The lava field was not examined in detail because of poor access and difficult terrain; however, both the rough, clinkery aa lava and the smooth-crusted, ropy pahoehoe lava were noted at the edge of the flow.

One or more cinder cones top this lava shield and probably were formed during the last eruptive phases. Two "steptoes" or islands of older rock were seen within the eastern part of the lava field when viewed from the top of the northernmost cinder cone in the Four Craters field.

The Devils Garden

The Devils Garden area covers about 45 square miles of the northern part of the Fort Rock Valley in northern Lake County, mainly in Ts. 24 and 25 S., R. 15 E. Thin flows of black pahoehoe lavas originating from fissures in the north and northeast part spread to the south and southwest. Several rounded hills and higher areas are islands or "steptoes" completely surrounded by the fresh black lavas.

Excellent examples of smooth, ropy pahoehoe lava are common on the upper surfaces of the large slabs formed by collapse when the hot fluid lava of the flows was drained from beneath thin, solidified crusts (Figure 3).

Along the northeast edge of the Devils Garden, there are classic examples of spatter cones, spatter ramparts, and lava tubes. Figure 4 shows one of two especially large spatter cones, locally called "the blowouts," in sec. 12, T. 24 S., R. 15 E. These were built over a fissure from temporary vents by the bubbling up of pasty clots of semi-molten lava. Another group of these spatter cones (Figures 5 and 6) aligned along a fissure are situated about a mile to the north.

Figure 7 shows the collapsed roof near the entrance to a very interesting lava tube that has been named "Derrick Cave." In some places the height to the roof is more than 50 feet, indicating that the formation of all lava tubes is not as simple as presently explained. Certainly the flow, whose top and sides cooled and later drained owing to pressure of the contained hot fluid lava on its snout, was narrow and thick. Numerous flat benches (Figure 8) on the tube walls show that the drainage of the tube was not continuous but stood still or flowed sluggishly at times. Further study of this lava tube, in which so many primary flow features are preserved, could give valuable information about how they are formed.

Lava Butte area

Lava Butte is situated alongside U. S. Highway 97 about 10 miles south of Bend and is a well-known feature to anyone who has travelled by. A road leading from the highway spirals around this classic, basaltic cinder cone to a parking area at the top. A well-formed crater exists at the apex of this cone and the lava field some 500 feet below can be viewed from its rim. Clinkery aa lava (Figure 9) erupted from a vent at the foot of the cone on the southern side and flowed to the west and northward for about 6 miles, blanketing an area of about 12 square miles. As it was extruded, this flow diverted and dammed the Deschutes River. The gutter through which lava flowed may be seen by following a trail of wooden planks, called the Phil Brogan Trail, which proceeds from the road at the bottom of Lava Butte over the rough lava surface to a viewpoint.

Across the highway to the southeast from Lava Butte is a small area of agglutinated spatter features that are aligned along the same fissure which fed the lava to Lava Butte and its lava field. These features were formed by semi-molten clots of lava thrown out by "fire fountaining" to build irregular mounds.

Figure 10 is a photograph of the quarry cut into Finley Butte, which lies some 12 miles south of Lava Butte. The picture shows the typical structure of a cinder cone, with beds of cinders lying at the angle of repose, about 32 to 35 degrees. Lava Butte would also show this same structure if its slopes were quarried.

Newberry Volcano (Paulina Mountains)

Newberry Volcano, with its large caldera, crater lakes, pumice and

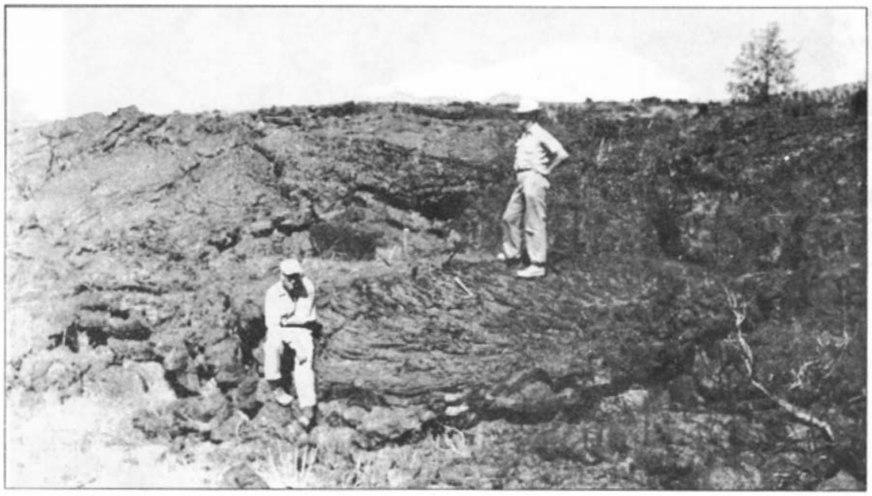

Fig. 3. Typical pahoehoe lava surface on eastern edge of Devils Garden lava field. Hot fluid lava flowed from beneath the cooled crust, causing it to collapse and break into a jumbled mass of slabs.

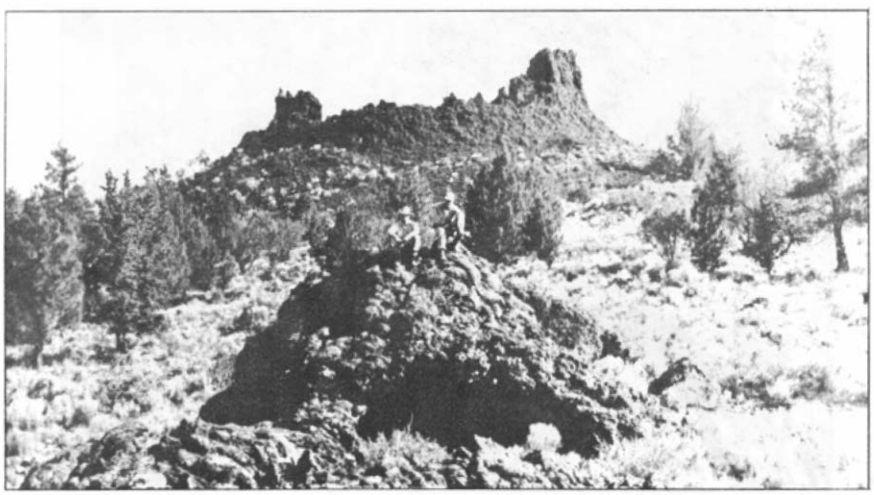

Fig. 4. Small spatter cone is disclosed in foreground. In background is an unusually large spatter cone, one of the "Blowouts." Another is hidden behind it.

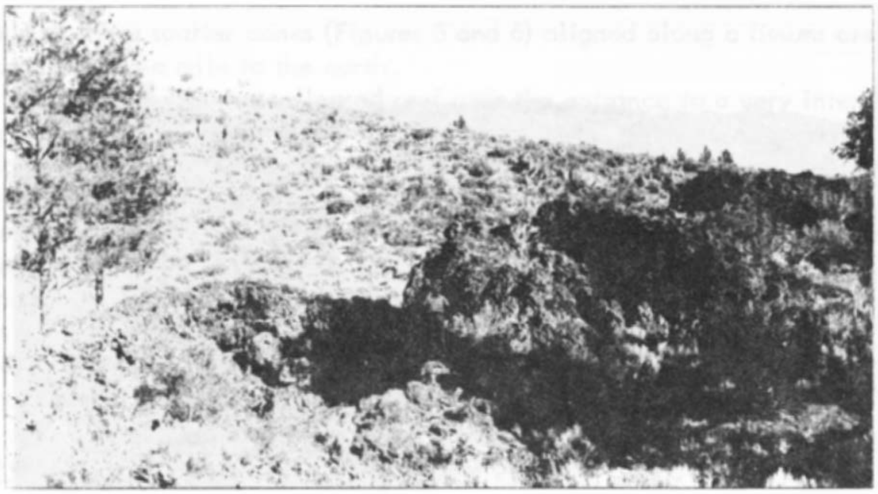

Fig. 5. A row of spatter cones aligned along a northwest-trending fissure, which crosses photograph from left to right.

Fig. 6. Detail of flow lines on spatter cone at upper end of row in figure 5. Semi-molten clots of basaltic lava were thrown out and piled on one another to form this feature. Note freshness of lava.

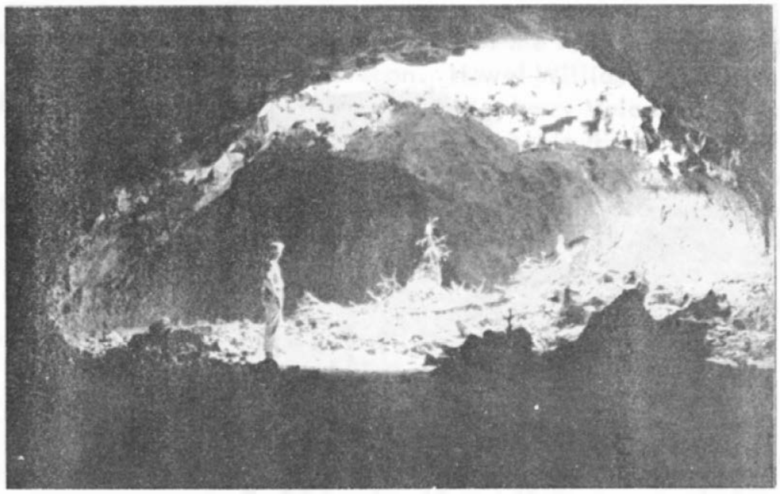

Fig. 7. This photograph was taken a short distance inside entrance of Derrick Cave. The roof has collapsed, allowing light to disclose shape of upper half of this lava tube. Debris from roof fills lower half of cave in foreground.

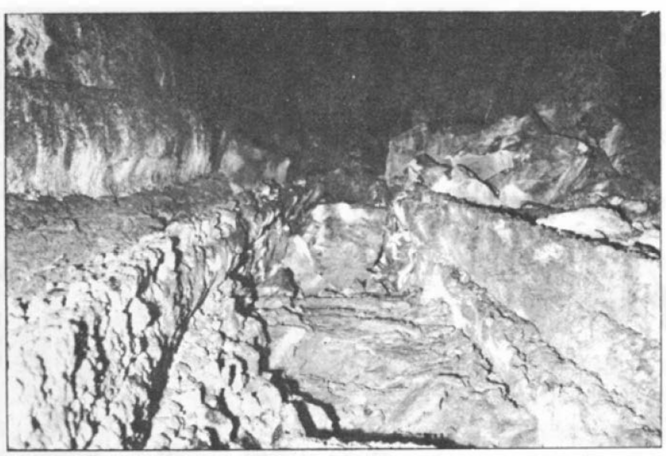

Fig. 8. This photograph taken far back in Derrick Cave displays several benches where lava remained at a temporary level as it flowed from the tube, some of it congealing along the sides. A gutter through which the last of the lava drained is seen in foreground.

Fig. 9. Clinkery or aa surface of Lava Butte lava field in foreground. Looking eastward, cinder cone of Lava Butte is in background. Lava issued from a vent at the base of cone, which is at the r in the photograph.

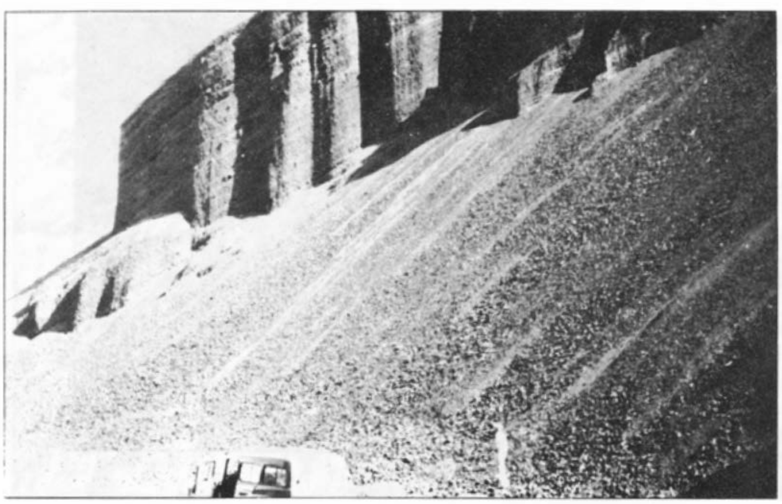

Fig. 10. Quarry cut into Finley Butte shows bedding of cinders and bombs of a typical basaltic cinder cone. Successive ejections of these pyroclastics produced the beds which lie at angle of repose. Lava Butte has a similar structure.

cinder cones, and domes of obsidian is one of the largest and most spectacular volcanic areas in central Oregon. Howel Williams (1935) has adequately described many of the features of Newberry Volcano. However, there are at least 150 small subsidiary cones on Newberry Volcano and many that have not been described in detail. Further study of these would seem to be warranted, since a large percentage of the cones and several lava fields, including Lava Cast Forest, are undoubtedly of Recent age. Of interest also are the several lava tubes situated about the flanks of Newberry Volcano. Probably many more of these tubes exist and will eventually be discovered.

Hole-in-the-Ground

Southward beyond the edge of the broad shield of Newberry Volcano are two young craters in T. 25 S., Rs. 12 and 13 E. that should be mentioned because of their resemblance to smaller lunar craters. Hole-in-the-Ground and Big Hole are maar-type craters that are believed to be formed by a series of brief, violent eruptions when rising basaltic magma encounters water or water-saturated rocks near the surface. These and other maar-type features have been described by Peterson and Groh (1961).

Is New Volcanism to be Expected?

Observation of the numerous volcanic cones, flows, and other features which have been formed by eruptions within the last 11,000 years, many within the last millenium, and some almost to the present, calls for wonder. The question then comes to mind: Will new eruptions take place in the near future - the far-off future?

Oregon, along with the other Western States, is within the zone of volcanic activity which surrounds the Pacific Ocean. Several hundred volcanoes in various phases of activity occur in this circum-Pacific belt. This "belt of fire" is also noted for its seismic (earthquake) activity, which signifies mobility of the earth's crust along this zone.

Volcanic and seismic processes in different segments of this belt have varied greatly in intensity throughout past geologic time and also in historic time. For the present, Oregon is enjoying a stage when activity within its segment is probably at its least. Therefore, volcanism in Oregon should be considered only as dormant, not extinct.

Renewal of volcanism in Oregon could well begin next month - this year - next year - or thousands of years hence. That is to say, its occurrence is not predictable in the light of our present-day geologic knowledge.

New eruptions, should they begin, probably would occur in the areas of most recent activity. The dominant zone of Recent volcanism trending northwest from the Four Craters area to that of the Three Sisters, as previously mentioned, would seem to be most favorable in this respect. Nevertheless, the older volcanic monarchs of the Cascade Range, such as Mount Hood and Mount Jefferson should not be thought of as dead. History has demonstrated that numerous volcanoes considered extinct by the nearby inhabitants have become reactivated. Even calderas thought by most volcanologists to have expended the energy of their magma chambers have renewed activity. Consequently, Newberry Crater and Crater Lake, Oregon's outstanding examples of calderas, should not be considered extinct.

New volcanism, though, is signaled almost invariably by earth tremors of moderate to great intensity and of increasing frequency days to months ahead. Crustal movements allowing magma to ascend toward the surface and/or pressures generated by the ascending magma are thought to produce these seismic tremors. A network of seismic stations in addition to the two now existing in Oregon would quickly establish the spot from which these tremors were radiating. Thus the surface locality through which an eruption might occur would be defined. Inhabitants within the zone of danger could be warned and measures for their protection taken.

Conclusions

In this report, we have touched upon only a few of the unique or unusual volcanic landforms existing within the area of Recent volcanic rocks in central Oregon. For the geologist and volcanologist, and for students of these sciences, there is a wealth of features to be observed and from which to reconstruct the volcanic processes leading to their formation.

Similarly, researchers in our nation's manned lunar landing program are offered a great variety of forms which may be landscape features of the moon's surface. Various instrumented probes will determine more thoroughly the composition and texture of the moon's surface in the immediate future. If this surface is comparable to recent volcanic terrain on the earth, then this central Oregon region should be of great value to those who are developing the vehicles and training the men who will land and explore the moon.

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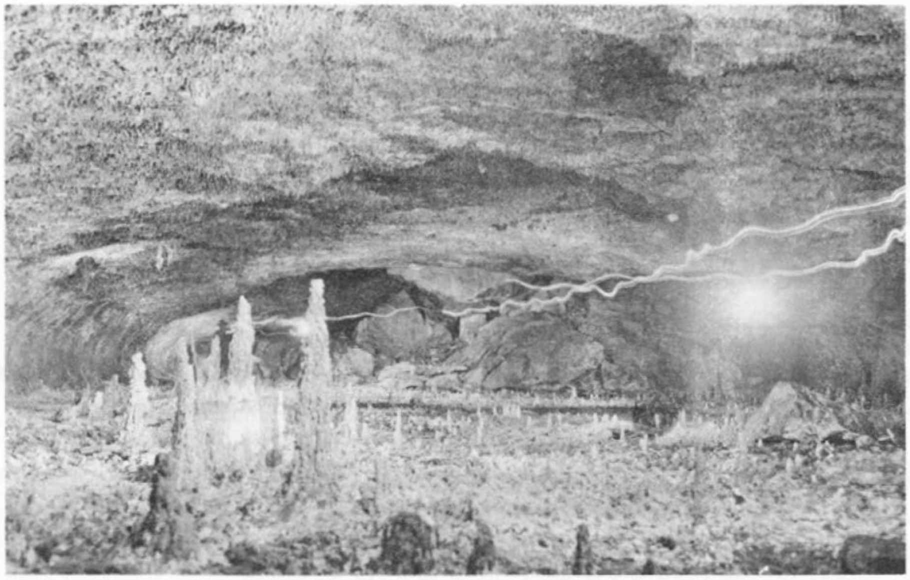

LAVACICLE CAVE

The picture was taken in Lavacicle Cave, a lava tube approximately 40 miles southeast of the town of Bend. Other lava tubes, such as Derrick Cave, Lava River Cave, and Skeleton Cave, are common in this part of central Oregon and undoubtedly there are a great many more yet to be discovered. Lavacicle Cave is unique because of the well-developed lava pinnacles rising from the floor. Phil Brogan, geological writer and editor of the Bend Bulletin, has suggested the term "lavacicle" for these distinctive formations. We are therefore proposing that this name be adopted for all such volcanic dripstones found in lava tubes.

Geologists have observed that certain lava tubes served as channelways for later lava flows. Evidence of these younger flows is seen along the walls in the form of projecting shelves and gutters, representing the various stages of flooding as the lava stream rose and fell. Apparently, Lavacicle Cave was temporarily filled to the roof by a younger flow. Immediately after this lava drained out of the tube, the molten material coating the ceiling dripped to the floor, building pinnacles of rock. The tallest lavacicle shown here is about 6 feet high; hundreds of others scattered over the floor range from 1 to 2 feet in height. In contrast, lavacicles on the ceiling are only a few inches in length.

Lavacicle Cave was found by accident in the summer of 1959 when a forest fire swept through that area. One of the fire fighters noticed a small hole in the ground, just large enough to crawl through. From it issued a stream of cold air. His curiosity concerning the source of the air current led to the discovery.

Until the time when the lavacicles can be properly protected from destruction by man, the U.S. Forest Service has closed the entrance, but permission to visit the cave can be obtained from the District Headquarters in Bend.

[Photograph by Dave Falconer]

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MAARS OF SOUTH-CENTRAL OREGON

By

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Introduction

If we could go back in time some 5 to 10 million years to the Pliocene Epoch and recreate the landscape of south-central Oregon, here are some of the things we would probably see:

From a plain originally of slight relief, faulting has already delineated broad basins containing large, shallow lakes. To the west, the High Cascade volcanoes are beginning to erupt on a grand scale. In and around the basins, volcanic vents, aligned along northwest-trending fissures, spew out fire fountains to form reddish-black scoria cones. These break through, spreading thin sheets of basaltic lava to fill depressions and further disrupt the existing drainage. When the basaltic magma rises beneath the lakes or near their borders, tremendous steam pressures are generated that trigger catastrophic initial explosions. Ash, lapilli, and large blocks of all the rocks involved are thrown high into the air in successive explosive eruptions to settle and to build raised rims of ejecta around the funnel-shaped craters. In some, the explosive phase dies quickly and fluid magma rises to fill the craters with a lava lake. In others the magma solidifies at depth, or withdraws, and water enters to form crater lakes. In still others, the same vents or ones nearby again explode violently to modify the original simple features.

Returning to the present, we see only the eroded and buried remnants of these peculiar volcanic features; our colorful reconstruction of the past had to be based on imagination and the little geologic evidence that remains.

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Distribution of Basaltic Tuff Landforms

During the summer of 1962, we made a broad reconnaissance of northern Klamath County and north-central Lake County to determine the distribution of the landforms described above to see if they form a pattern that would help to explain the special conditions necessary for their formation; we also looked for criteria that would make them easy to recognize.

The index map (pages 82 and 83) shows the distribution of basaltic tuff landforms that have been definitely recognized in the field during this study and also during other assignments in Klamath and Lake Counties in 1959, 1960, and 1961.

There are concentrations in two broad northwest-trending zones, one in the Fort Rock-Christmas Lake valleys in northern Lake County and the other in the Yonna and Sprague River valleys of central Klamath County. Individual occurrences and small groups of occurrences have also been identified adjacent to the Klamath River west of Keno and in the southern Fremont Mountains north and west of Lakeview, Oregon.

Future study will be extended to the south and east to cover the area bounded by Summer, Abert, and Alkali Lakes, and more detailed studies will be made of the individual landforms already recognized, to determine their original structures and origins.

Definition of terms

Maar, dry maar, ubehebe, tuff cone, tuff ring, and diatreme have all been used by various authors to describe relatively large, shallow, flat-floored craters that resulted from short-lived volcanic explosions.

Maar: As defined in the American Geological Institute glossary, a maar is "a relatively shallow flat-floored explosion crater, the walls of which consist largely or entirely of loose fragments of the country rock and only partly of essential, magmatic ejecta. Maars are apparently the result of a single violent volcanic explosion, probably of phreatic origin. Where they intersect the water table, they are usually filled with water and form natural lakes. The term was originally applied to craters of this nature in the Eifel district of Germany."

Dry maar or ubehebe: These terms have been used by Cotton (1941) to describe two small craters in Death Valley, California. These craters have raised rims built of layers of rock fragments derived from the immediately underlying terrain.

Tuff cone or tuff ring: These are synonymous terms for volcanic cones built primarily of consolidated ash and generally shaped something like a saucer, with a rim in the form of a wide circle and a broad central depression often nearly at the same elevation as the surrounding country. They usually show maximum growth on the leeward side. Individual tuff beds forming the cone dip both inward and outward, those in the high part of the rim approaching the angle of repose. Tuff cones are believed to be the result of hydroexplosions caused when lava erupts under water or water-saturated rocks close to the surface. In form tuff cones, or tuff rings, bear a general resemblance to maars.

Diatreme: A general term given to funnel-shaped or pipelike volcanic vents that are filled with angular fragments of many sizes of the rock types through which the pipe passes. In some there is no trace of magmatic material, but in others basaltic tuffs are present. An explosion crater is the surface expression of a diatreme. The term should probably be restricted to eroded features where only the pipe or the pipe-filling breccia remains.

The term maar is becoming more popular and is being used increasingly to describe these explosion craters with rims built of volcanic tuffs and breccias, even though no lakes were present. The term is also utilized for the volcanic processes that form this type of crater.

Tuff cone (or tuff ring) seems to be a more descriptive term, however, and is probably more nearly correct for describing the south-central Oregon structures where high rims of layered tuffs and breccias are present. These two terms, then, maar and tuff ring will be used interchangeably for the features in south-central Oregon.

Maar or Tuff Ring Field Identification

General types

Most of the central Oregon maar/tuff-ring features are similar and probably resulted from almost identical volcanic explosive processes. On the basis of the ones examined so far, there are enough differences in individual occurrences so they can be classified into three general types:

1. Simple maars: Circular or roughly circular craters surrounded by rims made up of steeply dipping, thin to thick layers of pyroclastic rocks. Excellent examples of this type are Hole-in-the-Ground and Big Hole,

shown in figure 1. As this type becomes more dissected and its original crater obliterated, the layers of tuff are usually exposed as low, curving hogback ridges that show their original ring shape, or as bold cliffs with a roughly circular shape, such as Fort Rock, shown in figure 2.

2. Simple maars modified by later lava: In this type, the conditions necessary for violent explosive activity ceased after a time, and the craters were filled by quiet extrusion with basaltic lava, which in some cases overflowed the rims and poured down the sides. Erosion of this type results in a lava-capped hill or butte surrounded by inward-dipping layers of explosion tuffs. Typical of maars of this type in the Fort Rock valley are Flat Top, shown in figure 3, and Table Mountain, in figure 4.

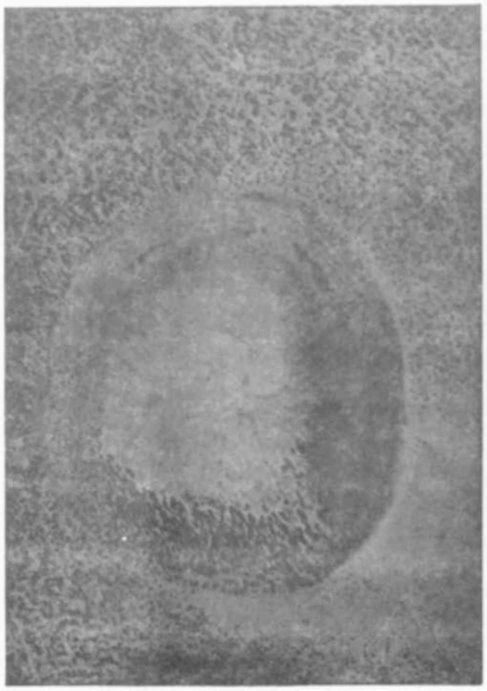
3. Complex maars: Where individual explosive vents were closely aligned or spaced, the tuff layers from separate explosions are superimposed on one another. Erosion of these complexes results in oval to elongate ridges of the layered tuffs with anomalous attitudes. A good example of this type can be seen in the large mass which makes up Table Rock near Silver Lake. This massive ridge is about 5 miles long and $3\frac{1}{2}$ miles wide and covers about 15 square miles with bold erosional outcrops of layered basaltic explosion tuffs.

Surface expression

The landforms that still retain crater depressions are the easiest to recognize, and so far two have been found in the Fort Rock-Christmas Lake valley. Hole-in-the-Ground has a crater almost a mile in diameter and Big Hole, $1\frac{1}{2}$ miles in diameter. Williams (1935) has reported three tuff rings within the Newberry caldera, one of which still has a saucer-shaped crater. The surface expression of eroded outcrops of the others examined indicates that this size is probably about the minimum, and where they occur in clusters they formed much larger masses.

Thickness of the layered tuffs

The layered tuffs and breccias at the rim crest of Hole-in-the-Ground are only about 150 feet thick, and they thin rapidly in all directions away from the crater. At Fort Rock (figure 2) the eroded cliffs show at least 300 feet of the thinly layered tuffs, indicating that either it was originally much larger than Hole-in-the-Ground, or that it had higher rims. At Table Rock near Silver Lake, the explosion tuffs make up most of the highest point, which is more than 1,000 feet above the surrounding plain.



(a)

(b)

Figure 1. Examples of typical simple maars. (a) Aerial view of Hole-in-the-Ground, showing truncated edges of the older rocks through which the vent was drilled. A small lake probably once filled the crater. (b) Aerial view of Big Hole. Walls and rim are composed entirely of thin layers of basaltic lapilli tuffs and breccias. Crater depression is broad and shallow.

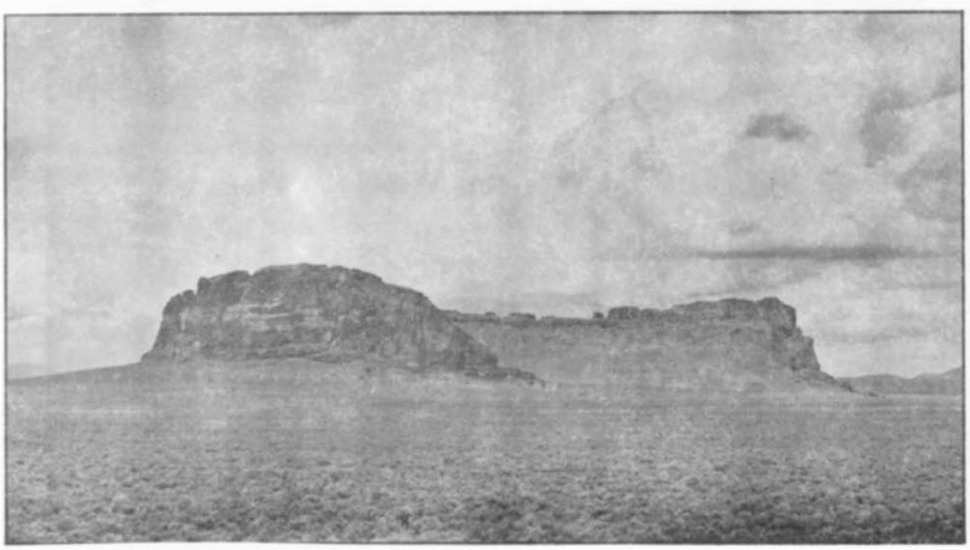


Figure 2. Fort Rock, an eroded remnant of a once much larger maar. The steep cliffs expose hundreds of thin layers of typical basaltic explosion tuffs. Well developed wave-cut terraces were formed by Pleistocene lake.

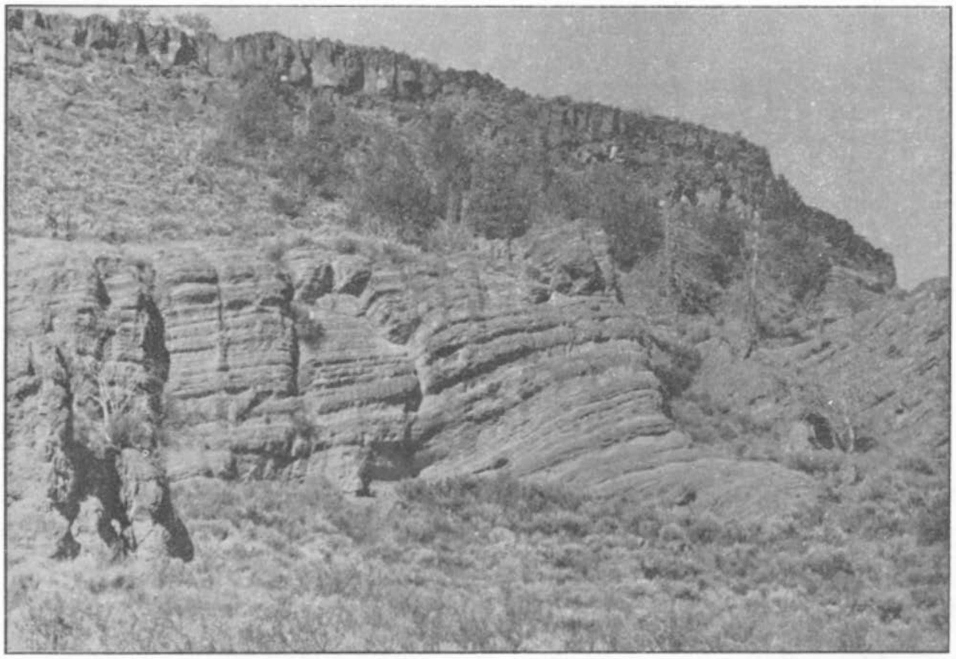


Figure 3. Flat Top, a remnant of a modified, simple moor. Layers of tawny basaltic tuffs dip beneath a basalt capping that originally filled the crater.

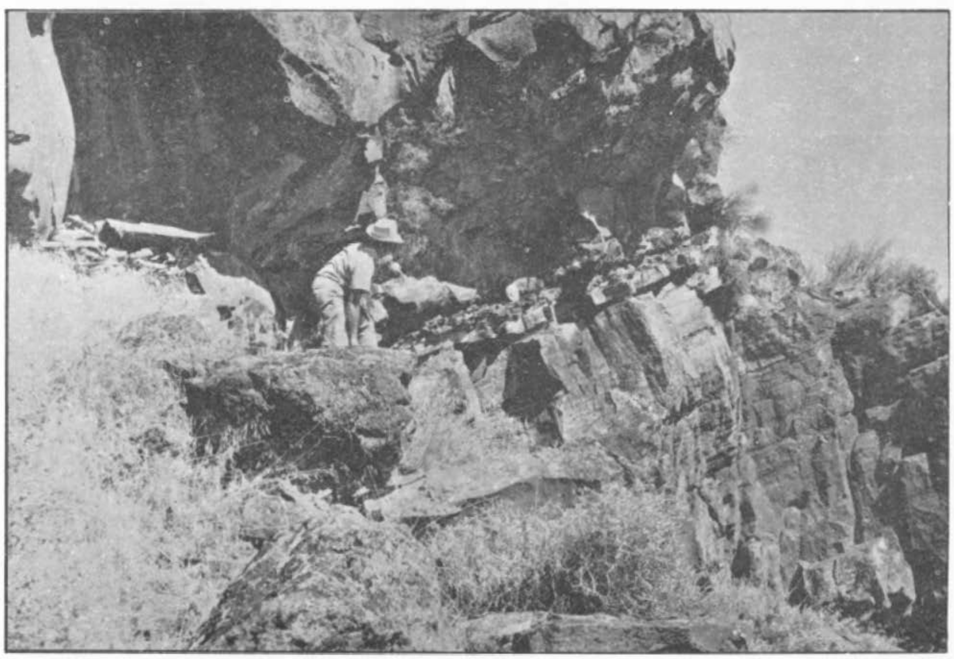


Figure 4. Table Mountain, illustrating a closer view of the contact of crater-filling lava with slightly baked, undisturbed tuffs which dip inward toward the crater.

Composition and structure of the tuffs

Thin layers of vitric lithic tuffs are present in all the maar/tuff-ring features and are perhaps the best criteria for their identification. Colors range from gray to drab yellows and browns, but are usually tawny. Tuffs of this type are composed of a variety of angular volcanic rock fragments in a matrix of fine, frothy basaltic glass. The fragments vary in size from microscopic shards to large blocks as much as 10 feet in diameter (figures 5 and 6), with lapilli sizes most abundant. The glassy nature of the groundmass in most of the explosion tuffs is easily recognized with a hand lens.

The tuffs and breccias almost always show a thin layering even though the rock fragments are large. This layering results from powerful sporadic showers of ejected material that drop directly into place. Cross bedding, channeling, and other sedimentary features resembling those of waterlaid deposits are locally present. Some layers are deformed by the larger fragments and blocks that have fallen directly on them.

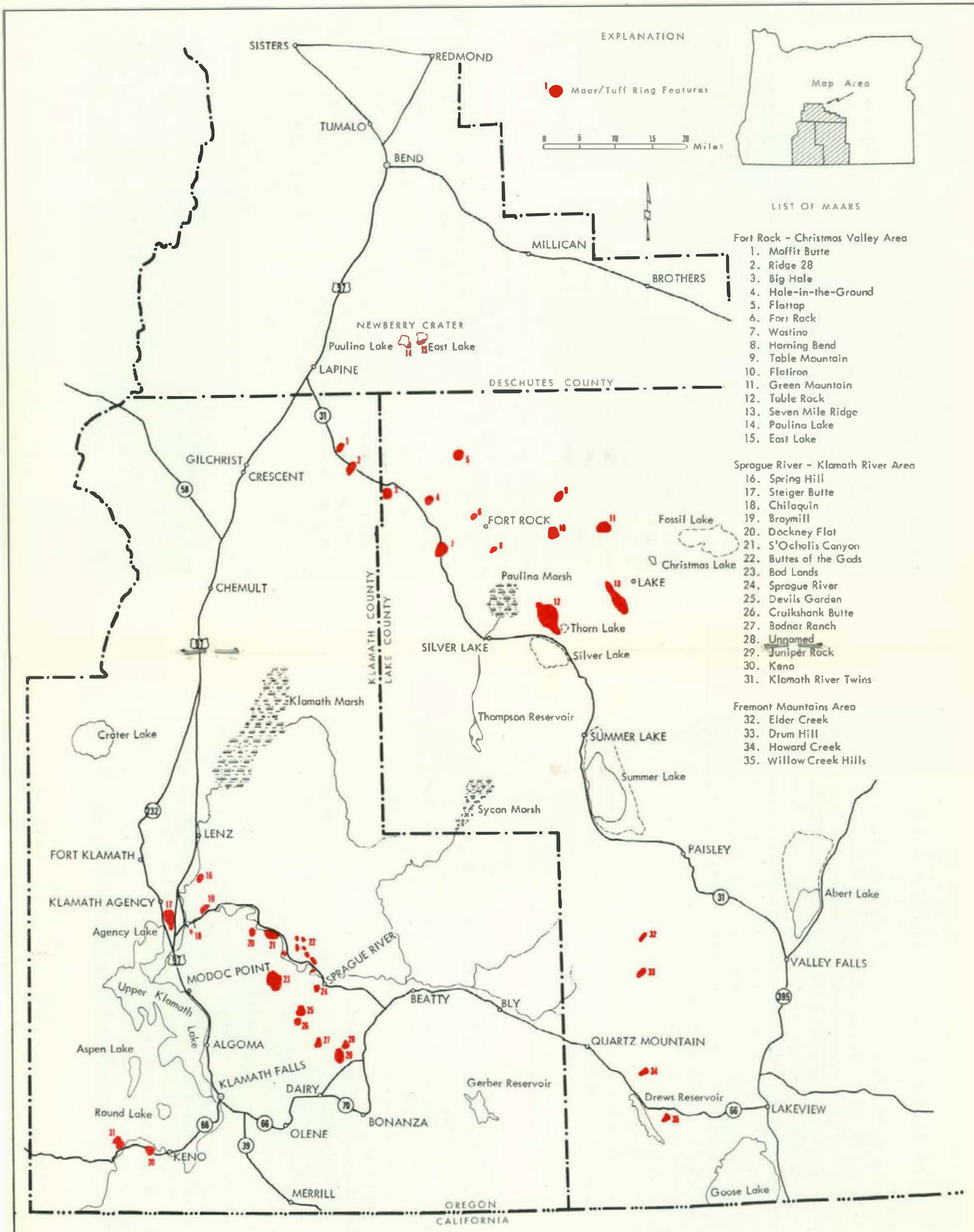
Dips are steepest at rim crests and some approach 30 degrees, which is probably near the angle of repose for fragmental rocks such as these. Inward dipping tuffs may be seen at both Flat Top and at Table Mountain (figures 3 and 4), where they have been protected from erosion by a capping of lava that filled the original craters of broad tuff rings.

The quaquaversal dips of differentially eroded layers of tuff can usually be seen even where dissection has been intense (figure 2). The comminuted ash from the explosions may have been very hot, and there may have been slight initial fusing or sintering in some of the layers. The moist environment and pozzolanic nature of the groundmass also may have resulted in almost immediate induration of the tuff layers.

In some places hoodoos, pedestals, and other irregular shapes so typical of badlands topography are formed by differential erosion. At Moffitt Butte adjacent to Oregon highway 31 these erosional features are common (figure 7).

Microscopic character

Brief examinations of a few thin sections reveal that the groundmass is made up of microvesicular basaltic glass fragments and shards which are almost completely altered to palagonite. Small, broken crystals of calcic feldspar and olivine are also present. Round vesicles are abundant (figure 8), and many of them, as well as the voids between the shards, are filled with calcite and zeolites.



DISTRIBUTION OF MAARS IN SOUTH-CENTRAL OREGON

Volcanic Processes in Maar Formation

A review of the literature on maars in other regions of the United States and elsewhere in the world brings out four common characteristics: (1) maars have occurred in a hydrous environment, with surface water or a high water table present during their eruptive history; (2) a distinctive layering of the ejecta made up of both magmatic and accidental material indicates that they were formed by relatively short, successive explosive ejections; (3) there are present accidental rock fragments, some quite large, which have been brought up from a considerable depth by the expulsion of large quantities of gases through the conduit or diatreme from the underlying magma source; and (4) the composition of the magmatic addition is generally mafic, in many cases an alkalic type basalt.

Any satisfactory explanation of the mechanisms or processes for the formation of maar-type volcanoes should recognize these four criteria. Numerous authors have advanced theories of maar formation ranging from the gaseous emissions of a magma to steam explosion due solely to contact of meteoric water with hot magma at depth. Others tend to the collapse, or caldera, hypothesis as the main process after the formation of a tuff ring. In general, most authors seem to recognize that explosive eruptions are involved.

Shoemaker (1962) believes the gases from a magma, once they have drilled a vent or diatreme to the surface, go into a state of surging similar to the action of a geyser. He does not consider the presence of water as significant. The violent emission of these gases enlarges the conduit providing the accidental ejecta, and with additions from the magma builds the maar; subsequent subsidence and slumping enlarges the crater after eruptive activity has ceased.

Stearns (Stearns and Vaksvik, 1935), on the other hand, believes the contact of hot intruding magma with surface water or water-saturated rock is the main causal agent. He envisions a catastrophic explosion by this method which produces the initial crater. Material collapsing from the crater tends to plug the vent, then, with the entrance of more water, another steam blast occurs as contact is made with heated rock. Coupled with this is the sudden relief of pressure on the magma column, setting up a violent vesiculation which produces the pyroclastic component. This is repeated until the energy supplied by the magma is exhausted. Cited also in support of this "phreatomagmatic" origin of the Oahu, Hawaii, maars is the fact that all occur close to the sea. Stearns (1926) also has noted the relationship of maars and ground water in the Mud Lake area of Idaho. Lee (1907) believed this same mechanism to be the cause of the Afton Craters,

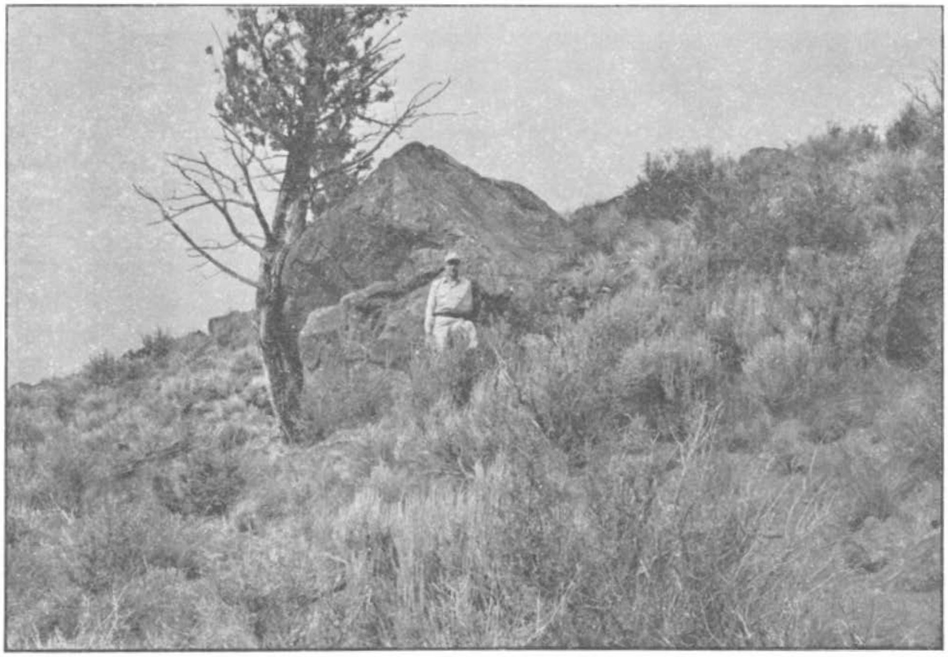


Figure 5. Enormous accidental block of porphyritic basalt lying near the crest of the east rim of Hole-in-the-Ground.

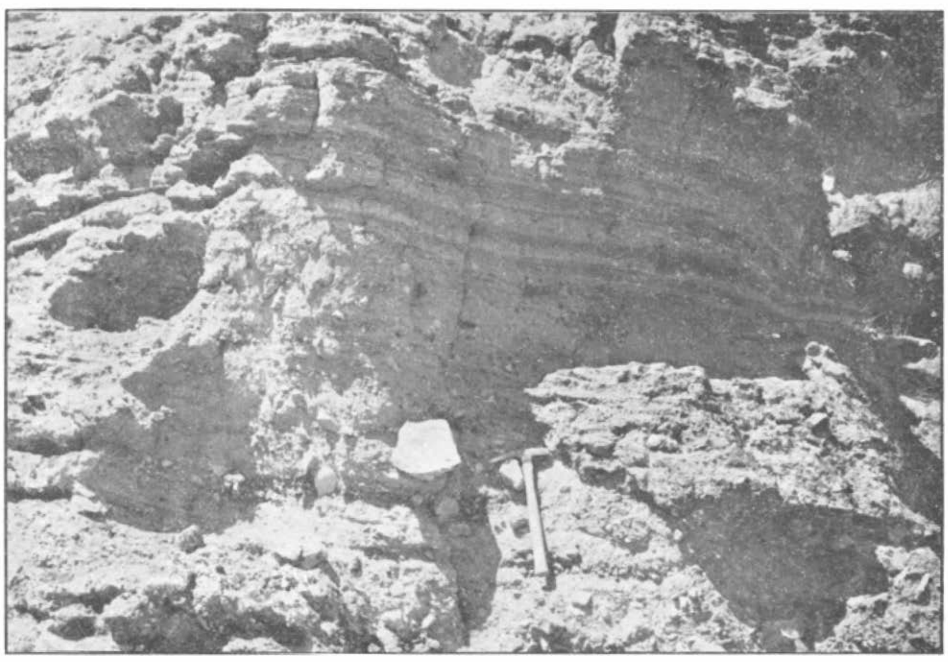


Figure 6. Closeup of Horning Bend showing thin layers and intimate mixing of angular rock fragments. The tuffs at this location contain a high percentage of accidental glassy rhyolite.

Figure 7. Hoodoo and badlands type of erosional landforms at Moffitt Butte. These and other differential weathering features are characteristic.

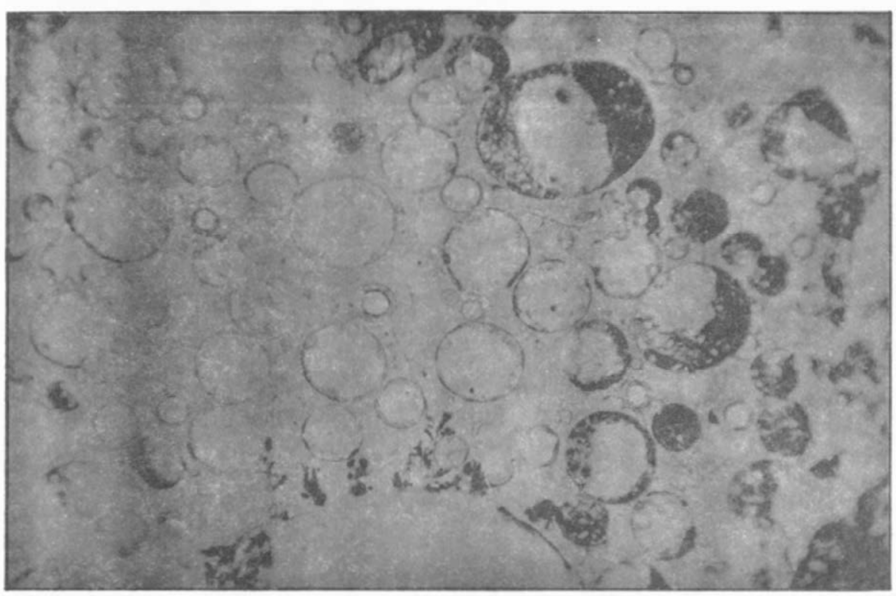


Figure 8. Micro-photograph of basaltic (palagonite) tuff showing the microvesicular nature of the groundmass, which is composed of fragments and shards of yellow-brown basaltic glass.

New Mexico. In his study of the Hopi Buttes area diatremes, and remnant maars, Hack (1942) has postulated the "phreatomagmatic" origin of these features which are closely associated with the Pliocene sedimentation of that region.

Jahns (1959), in his study of the Pinacate Craters in Sonora, Mexico, postulates the formation of a large tuff breccia cone by explosive action of a vesiculating magma on a catastrophic scale. When this magmatic energy is expended, collapse and foundering into the partially evacuated magma chamber results in the formation of a caldera. Since the Pinacate Craters belt is confined to only a part of a large volcanic field containing hundreds of cinder cones. Jahns also cites Stearns' (Stearns and Vaksvik, 1935) theory as a possible alternate explanation.

A different view of the formation of a maar is offered by Mueller and Veyl (1957) by their observations of the eruption of a new maar called Nilahue Maar, in Chile. It is their contention that the pyroclastics making up the maar cone were formed from fusion of the rock originally contained in the crater by the enormous quantity of hot gases expelled and that no addition of magmatic material took place. Added to this was also unfused accidental ejecta of the rocks penetrated by the vent. Theorizing on the origin of the maar, they believe gases which accumulate at the top of an intruding magma erupt through the overlying rock and continue their spasmodic expulsions until exhausted. Surface water, and presumably ground water (although they do not specifically mention ground water), breaching the weak ash barrier and flowing into the vent help to keep it open by secondary steam blasts. Otherwise, in the absence of water, they believe a regular pyroclastic cone would be built which would place a damping effect on the gases escaping, this in turn allowing the cone to grow by keeping the ejecta close to the vent.

All of these hypotheses attempt to explain the causes for the characteristic features of maars, but there are still many questions which are not completely answered. The one point that most authors do agree on is that violent expulsion of gases is an important requirement in maar volcanism.

The writers' studies and field work on the maars discovered to date in south-central Oregon strongly point to a hydrous environment existing at the time of their formation. Many probably erupted into the shallow lakes present throughout this region during the Pliocene and Pleistocene epochs. Others were formed in the areas where the water table was near the surface around the lakes and in the drainage system of the region. In such an environment it can well be expected that magma and/or the volatiles heating fractured and porous water-bearing rock would produce a phreatic or steam explosion, throwing out this rock and forming a funnel-shaped crater, as advocated by Stearns (Stearns and Vaksvik, 1935). Corwin and Foster (1959) describe an explosive eruption on Iwo Jima which occurred in such a manner.

The numerous beds of crudely sorted ejecta which make up a maar or tuff ring indicate a similar number of ejecta falls, each expelled essentially as a unit. Each bed apparently was explosively ejected in a short interval of time with a relatively quiescent period between successive eruptions. The observations of Mueller and Veyl (1957) confirm this evidence. Yet these short, violent eruptions, of perhaps 20 or 30 minutes duration, do not seem to be satisfactorily explained solely by ground or surface water contacting heated rock, the magma, or its volatiles. After the initial phreatic explosion, the major share of energy must be derived from the magma, mainly its hot gases. Some mechanism that causes a plugging or stoppage between successive eruptions seems to be a necessary requirement. A point that has not been previously emphasized in the maar volcanic process is possibly the influence of the wide crater, a feature common to all maars. After phreatic eruption forms the initial crater, part of the fallback would tend to plug the vent until increased gas pressure could blow this material out again. As the crater widens with repeated new eruptions, a greater portion of the fallback is collected and funneled into the vent. Thus a temporary plugging by a load of loose material falling back into a wide crater may be of major importance in maar volcanism. Stearns (Stearns and Vaksvik, 1935) advocates a similar process of plugging by fallback, but does not consider the importance of a wide crater in relation to this action. The infiltration of surface and ground water into the lower and hotter portion of the vent may help to produce steam blasts causing further fragmentation of the rock and adding some energy during eruptions. Crater diameter enlarges to a size which is related to the maximum energy expended in the eruptive process.

With each eruption, tremendous volumes of gases must be generated by an explosive frothing of the magma. A fluid, mafic magma carrying volatiles would permit this action more readily than a viscous one. This would account for the glassy, vesicular ash of basaltic composition typically present as the magmatic addition in the maars of south-central Oregon. Expulsion of a large volume of gases also can be expected to provide a high velocity streaming through the conduit. This streaming of gases carries rock broken from the walls up the conduit. Some quite large blocks are brought from considerable depths in this manner. Fragments of rock transported from depths of several thousand feet have been reported in studies of maars and diatremes of other localities (Hack, 1942, and Shoemaker, 1956). The fragments are probably brought to the surface during one single eruption, although some may fall back and require two or more eruptive episodes. As previously mentioned, the writers' study of Hole-in-the-Ground has pointed out that some enormous blocks have been carried up from depths of at least several hundred feet (fig. 5).

After all volcanism ceases, the diameter of the crater is further increased by subsidence and compaction of the material in the vent, slump of the crater walls, and normal erosion.

Conclusions

A wide distribution of maars/tuff rings occurs throughout south-central Oregon, and the evidence shows an association with a hydrous setting at the time of their formation. Studies of the Pliocene-Pleistocene rocks of areas not as yet examined in this region will no doubt expose many more of these features. At present, these peculiar volcanic structures show a pattern along two rather broad, northwest-trending zones which is also, as expected, the major direction for the faults of this region. As additional maars are discovered, some modification of this pattern may be noted.

Since accidental fragments in the tuff-breccia beds of these maars have been expelled from a conduit or diatreme, they provide a rough sample of a section of the underlying rocks. Petrographic study of these fragments, some of which may have been brought up from depths of several thousand feet, can confirm whether a certain known rock formation exists below. This may aid the geologist, for instance, in solving a structural problem when mapping a particular area in the vicinity of a maar.

Many hypotheses for the volcanic processes of maar formation have been offered by various writers from their observations of these features. Generally, all who have studied maars or tuff rings agree that explosive eruptions are necessary to their production. The almost universal association of maars with a water-bearing environment seems also to be an essential factor. Relating this factor to the explosive volcanic process which forms a maar leaves many questions unsatisfactorily answered. The maars of south-central Oregon, ranging from those little eroded to those completely dissected, present an unusual opportunity for study.

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THE AGE OF CLEAR LAKE, OREGON

By G. T. Benson*

Clear Lake, in Linn County, is located at the head of the McKenzie River, about seven miles west of the crest of the Cascade Range between Santiam and McKenzie Passes (see accompanying map). The lake, which is close to U.S. Highway 126, is noted for its drowned forest; tall trees still standing on the lake bottom are easily seen in the cold, clear water.

The lake was formed when a lava flow poured into the upper McKenzie Valley, damming the river and ponding its water. The lava came from one of the vents marked by the Sand Mountain line of craters (Williams, 1957). This basalt flow is part of the group of young volcanic rocks in the Santiam-McKenzie Pass area shown on the map. That this volcanism occurred a geologically short time ago is evident from the lack of soil and vegetation on the flows.

The dramatic sight of miles of bare, jumbled lava at McKenzie Pass (see photograph) has long caught the fancy of motorists. To increase the benefit of the area to the public, the U.S. Forest Service is preparing exhibits explaining the geology in the vicinity of Dee Wright Observatory at the Pass. In the course of planning the Forest Service project, the question of the absolute age of the flows at McKenzie Pass was raised. It was apparent that an answer might be obtained from radiocarbon dating.

Carbon-14, a radioactive carbon isotope with a half-life of about 5,570 years, is produced continuously in the atmosphere by cosmic-ray bombardment. The rates of production and decay result in an equilibrium concentration of radiocarbon, or, stated differently, in an equilibrium ratio between radiocarbon and non-radiogenic carbon. Carbon in living tissue is constantly replaced, so that radiocarbon and non-radiogenic carbon are present in the equilibrium ratio. When the tissue dies, however, replacement ceases, and the ratio changes as the radiocarbon atoms decay. The difference between the ratio in dead tissue and the ratio in living tissue is a measure of how long ago the former died. In practice, the date of death of once-living tissue can be determined with adequate accuracy back to about 40,000 years before present (y. b. p.).

Charcoal from trees burned by the hot lava at McKenzie Pass could be used to date the flows. Several searches were made, but no charcoal that could be attributed definitely to burning by lava was found either in the

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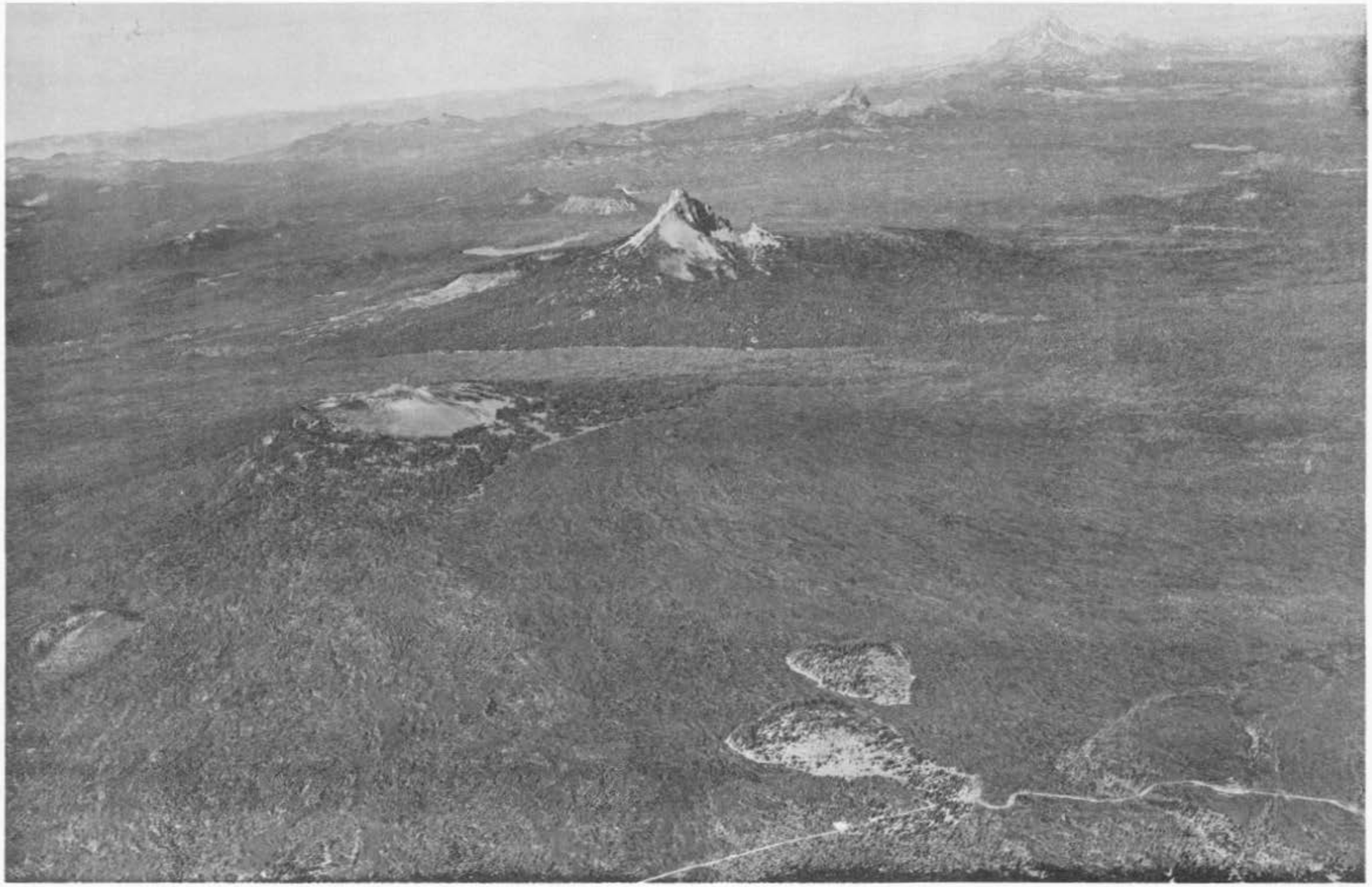

Aerial view of McKenzie Pass looking north toward Mt. Washington, Three Fingered Jack, and Mt. Jefferson. Belknap Craters and lava flows in foreground. (Courtesy of Delano Photographics)

RECENT LAVA FLOWS in the SANTIAM PASS-McKENZIE PASS AREA

flows from the Belknap Craters or in the flow from Yapoah Crater, upon which Dee Wright Observatory is located. A direct answer to the question of absolute age of the McKenzie Pass Lava flows must await the discovery of charcoal; but an indirect answer could be obtained from the trees in Clear Lake.

The U.S. Forest Service arranged to have members of the Whitewater Divers, a group of skin divers from Eugene, take samples of the drowned trees. Several sections of trees were obtained in November, 1963, in what must have been one of the first aqualung logging operations. Two samples from one section of a tree about one foot in diameter taken at a depth of about 13 feet below the surface were chosen for dating. The samples were analyzed by Isotopes, Inc., of Woodlawn, N.J., and dates were reported as follows: Sample a [3,200 ± 220 y.b.p.] sample from center of tree section; and Sample b [2,705 ± 200 y.b.p.] sample from outer part of tree section. The two dates appear to be in adequate agreement. Part of the differences should be due to locations of the samples in the tree section. From these dates, the trees in Clear Lake can be said to have drowned about 3,000 years ago, when the lake was formed by the lava flow from Sand Mountain.

As shown on the map, three groups of lava flows have been delineated through the use of aerial photographs. The oldest is the Sand Mountain flow, which we now know is about 3,000 years old. Lava flows from Belknap Crater lap onto flows from Sand Mountain, and thus are younger. On the basis of superposition and lack of vegetation, the lavas from Little Belknap Crater which are so conspicuous at McKenzie Pass, are the youngest of the flows from the Belknap Craters. But even these lavas are not the most recent. The Dee Wright flow from Yapoah Crater overlaps the Little Belknap flows and is therefore younger, as are the flows from Collier and Four-In-One Craters.

Thus, by knowing the age of Clear Lake and the lava flow that formed it, we can say that the lava at McKenzie Pass is less than 3,000 years old, and some of it is considerably younger. Determining the absolute age of this freshest lava requires discovery of charcoal and carbon-14 dating.

Reference

Williams, Howel, 1957, A geologic map of the Bend quadrangle and a reconnaissance geologic map of the central portion of the High Cascade Mountains: Oregon Dept. of Geology and Mineral Industries map.

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HOLE-IN-THE-GROUND, CENTRAL OREGON
Meteorite Crater or Volcanic Explosion?

by

Norman V. Peterson* and Edward A. Groh**

Lewis McArthur, in Oregon Geographic Names, has described Hole-in-the-Ground as follows: "Hole-in-the-Ground, Lake County. This very remarkable place is well described by its name. It covers an area of about a quarter of a square mile, and its floor is over 300 feet below the surrounding land level. It is about eight miles northwest of Fort Rock."

Hole-in-the-Ground is a large, almost circular, bowl-shaped crater in the northwest corner of Lake County. It has a slightly elevated rim and looks very much like the famous Meteorite Crater in north-central Arizona. This remarkable resemblance and the lack of an explanation of the origin in the published literature was brought to the attention of the department by Groh and is the basis for the present study.

The original plans for the study included only Hole-in-the-Ground and the nearby larger, shallower crater, Big Hole, but very soon after arriving in the area the writers noticed other interesting volconic features of explosion origin. These features, shown on the index map (figure 1), include Fort Rock, Moffit Butte,

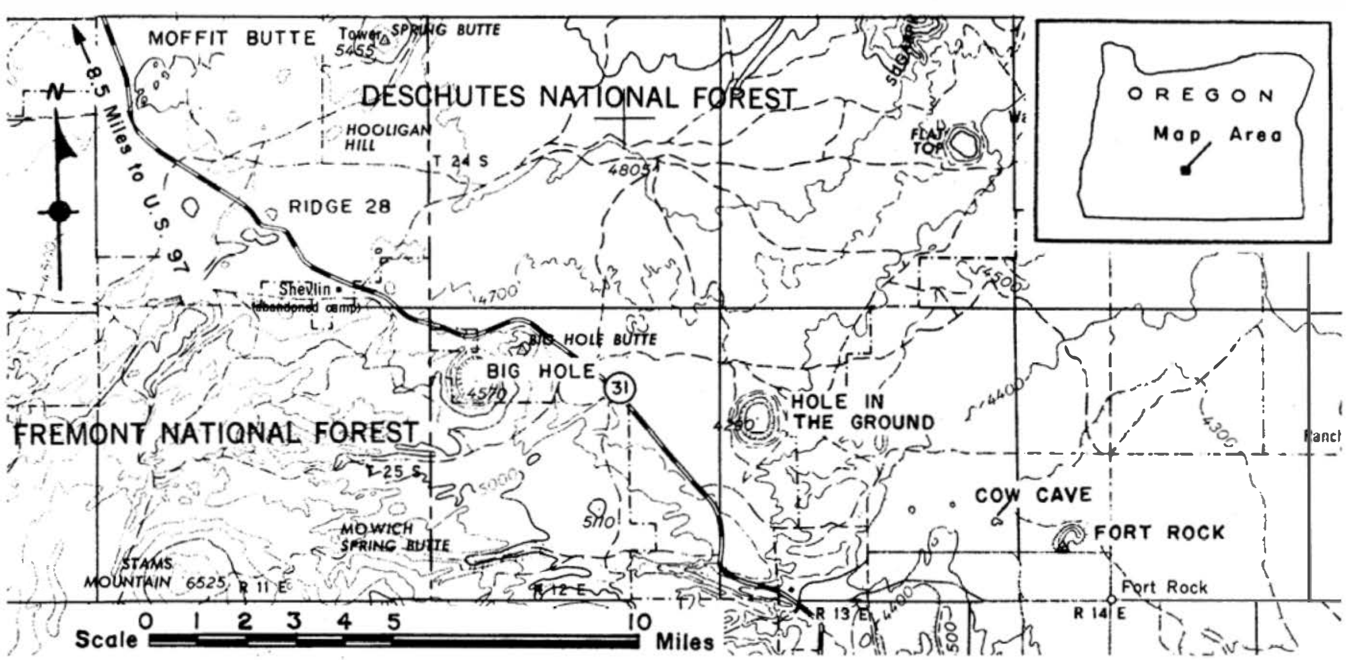

Figure 1. Index map of the Hole-in-the-Ground area, central Oregon.

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Flat Top, and several unnamed landforms north and west of Hole-in-the-Ground. All were examined and are described briefly in later paragraphs.

After a reconnaissance of the geology of the whole area was made, two days were spent studying the rocks in the walls and rim of the Hole-in-the-Ground crater and searching for evidences of meteoritic material.

Hole-in-the-Ground

Hole-in-the-Ground (figure 2) is in sec. 13, T. 25 S., R. 13 E., in the extreme northwestern corner of Lake County. It can be reached by turning east from Oregon Highway 31 on a well-marked Forest Service road 25 miles southeast of the junction with U.S. Highway 97 near Lapine, Oregon.

The depression or crater has many of the characteristics of a meteorite crater. It is almost circular with steep walls sloping to a flat floor that is about 425 feet below a raised rim. The highest point on the rim is at an elevation of 4800 feet, about 500 feet above the floor of the crater.

The resemblance between Hole-in-the-Ground and the Arizona meteorite crater is shown by the following comparison:

	"Hole-in-the-Ground"	"Meteorite Crater"
Diameter	5000'	4000'
Depth (crest of rim to crater floor)	425'	613'
Height of rim above surrounding plain	100' to 200'	148' to 223'
Rim slope to plain	about 5°	3° - 5° (½ mile)
Rock in walls	Basalt, ash flow, tuff, and explosion debris	Limestone and sandstone
Age	At least 2000 to 9000 years, based on dating of pumice falls from Newberry Crater and Mount Mazama (Crater Lake).	20,000 to 75,000 years.

The rocks that crop out in the walls of Hole-in-the-Ground are shown on the accompanying cross-section (figure 3) and are, from bottom to top, an ash flow tuff, a series of fine-grained light-gray olivine basalt flows, explosion tuffs that contain many types and colors of rock fragments, and large blocks as much as 10 feet in diameter of explosion debris including a conspicuous porphyritic olivine basalt that is believed to occur deeper than the rocks exposed in the crater walls. The floor, steep slopes, and rim are blanketed by pumice from Mount Mazama (Crater Lake) and Newberry Crater. A thin soil zone has developed on the pumice. The rim is slightly higher and broader to the east, indicating a westerly wind at the time of the explosion. A small fault offsets the basalt flow in the east wall of the crater.

The crater rim was carefully examined to determine if metallic meteoritic material, shattered rocks, deposits of rock flour, or minute metallic droplets of vaporized meteoritic nickel-iron were present. As the crater and explosion debris were already present when the latest pumice showers occurred, holes were dug to a level beneath the pumice and the soil screened and tested with strong magnets for the presence of metallic magnetic material. Magnetite from the pumice and underlying lavas and tuffs is abundant in the soil, but no identifiable meteoritic fragments or metallic droplets could be found. An examination of the outcrops of the basalt flows also did not show the great shattering and upward tilting that should accompany the explosion of a large meteorite.

It is almost certain that, if this crater were the result of a meteoritic impact explosion, fragments of nickel-iron and metallic droplets or their oxidized products would be present in abundance on and around the rim, as is the case at the Arizona Meteorite Crater. This should be true even for a stony meteorite, because they generally contain several percent of nickel-iron in metallic form. It is very doubtful if a large stony meteorite could survive passage through the atmosphere to produce a crater of this size; rather, the sudden

Figure 2. Hole-in-the-Ground, a late Pleistocene maar, viewed from the south. This crater is nearly a mile (1.6 km) in diameter and the highest point on the east rim is 500 feet (153 m) above the crater floor. Basalt flows exposed in the far wall underlie the explosion tuff breccias as shown in the geologic cross-section below (fig. 3).

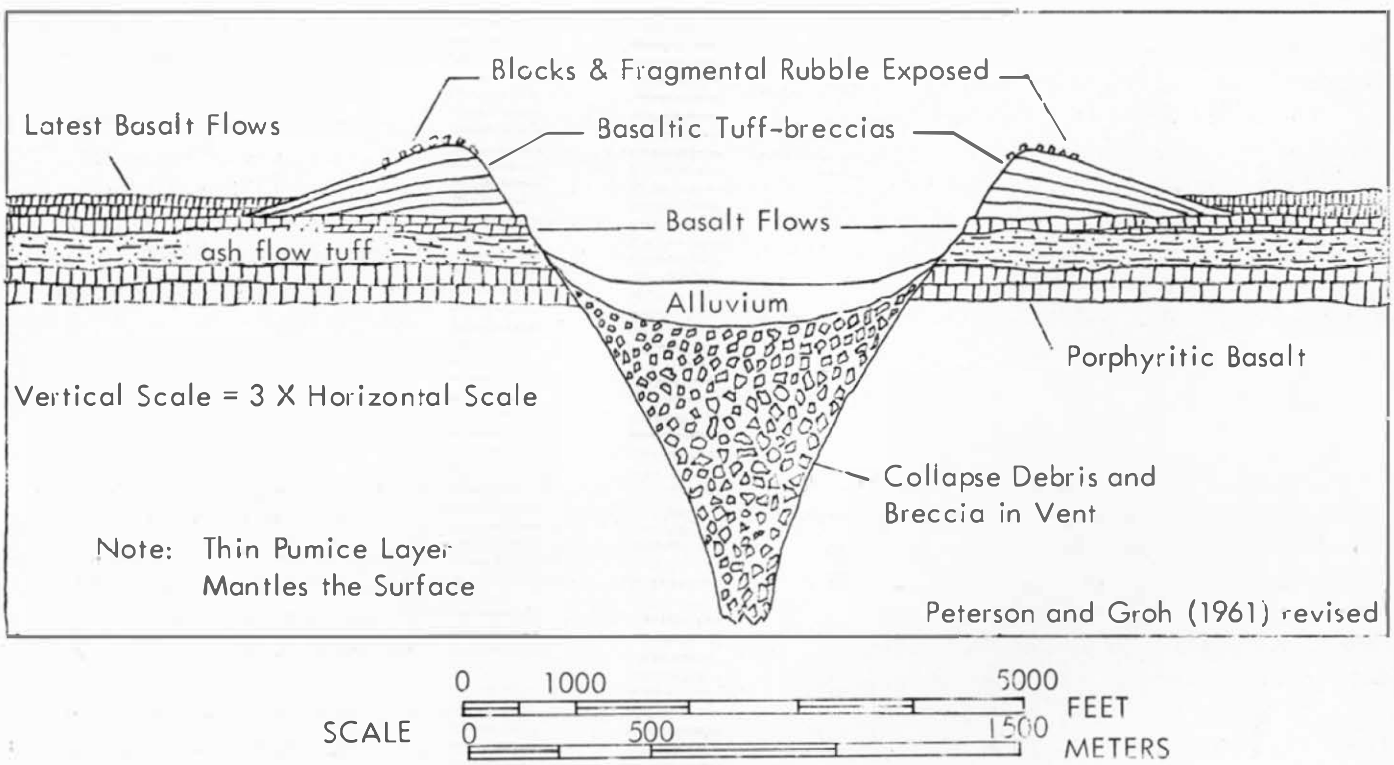

Figure 3. Generalized Geologic Cross Section of the Hole-in-the-Ground.

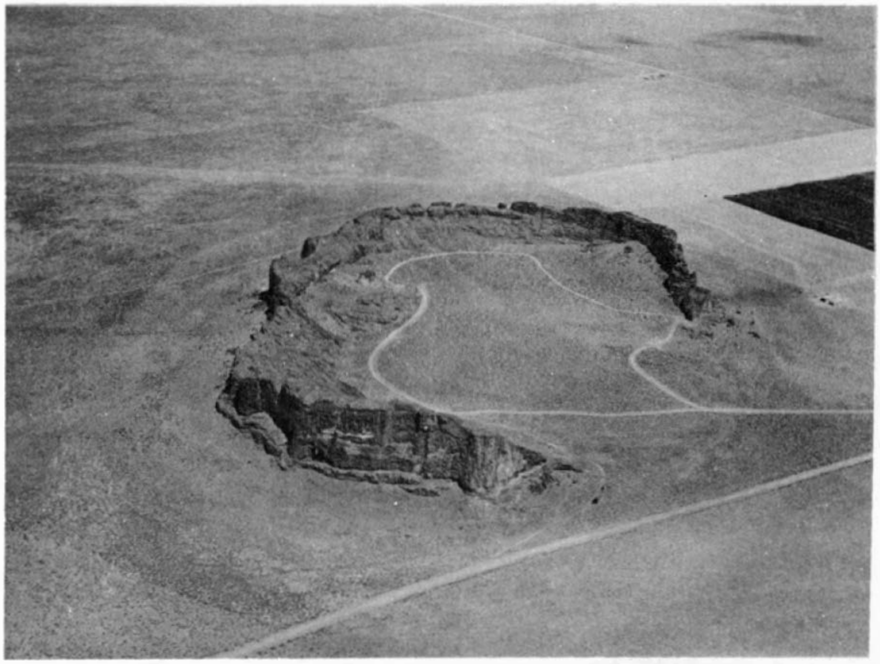

Figure 4. Aerial view of Fort Rock looking to the northeast. Differential weathering has accentuated bedding in nearest wall. This wall is a sheer cliff about 200 feet high and more than 300 feet above the plain. Pleistocene lake terraces have been cut into both ends of "horseshoe".

heat and pressure evolved upon encountering the denser air mass would cause the meteorite to break into many fragments. Only small craters or pits would result when these struck the earth.

In the absence of any positive evidence for its formation by meteorite impact, the location of the crater in an area of known recent volcanic activity and the many associated volcanic features point to an abrupt volcanic explosive origin for the Hole-in-the-Ground.

It is believed that Hole-in-the-Ground resulted from a single or a very brief series of violent explosions caused when rising magma suddenly came in contact with water-saturated rock. The source of the water could have been the extensive lake that once existed in Fort Rock Valley. The explosion blew out large quantities of older rocks, together with pyroclastic material, and formed an embryonic tuff ring. Apparently the magma withdrew after this brief activity and did not continue or return to eject additional pyroclastic material in the quantity for the formation of a large tuff ring. A detailed description of this process is given in the discussion of Big Hole, a similar but more fully developed feature.

Big Hole

This large depression, as shown on the index map, is in secs. 5, 6, 7, and 8, T. 25 S., R. 12 E. It is a broad shallow crater with walls and rim made up of dark-gray and brown lapilli explosion tuffs and breccias. These rocks dip outward from the center of the crater. The rims are not quite as well defined as at Hole-in-the-Ground and a heavy stand of timber within and around the crater makes detail difficult to see. Big Hole, however, is a much better developed tuff ring than Hole-in-the-Ground in that a greater volume of pyroclastic debris has accumulated around the rim. Although both craters are young geologic features, Big Hole appears to be the older. In other respects the two craters are alike.

The Big Hole tuff ring is very similar to the well-known Diamond Head tuff ring on Oahu, one of the Hawaiian Islands. A tuff ring or tuff cone is a broad-floored ring-enclosed volcanic crater. Such features typically have steep inner walls that show the edges of both inward and outward dipping layers of explosion tuffs and breccias. The ejected fragments have been dropped directly into place after being hurled high into the air. The tuffs and breccias are composed of consolidated heterogeneous mixtures of vitric material from the parent magma and fragments of previously formed rocks.

There is a very definite association of tuff rings with water, and they are believed to occur where intrusive magmas have come into contact with water-saturated rocks at shallow depths. Tuff rings are thought to be formed in a very short period of time (a few days to a few months) by a rapid series of explosions that eject fine ash and rock fragments high into the air. Each explosion is followed by slumping of the crater walls and rock falling directly back into the crater to form a plug; then water rushing into the crater furnishes the steam for another explosion. Crude gravity sorting of the particles that are dropped directly into place accounts for the distinct layered structure of the tuff rings.

Big Hole, Hole-in-the-Ground, and the other tuff ring features in the area may have been formed as far back as Pliocene time, but more likely during the Pleistocene or even Recent epochs when large pluvial lakes occupied valleys formed by block faulting. At the time these lakes existed there was sufficient ground water in the area to affect the intruding magma in the manner that has been described.

Eroded Remnants of Other Tuff Rings

Fort Rock

In Oregon Geographic Names, Lewis McArthur described Fort Rock as follows: "The rock is an isolated mass, imperfectly crescent shaped, nearly one-third of a mile across and its highest point is about 325 feet above the floor of the plain on which it stands. It has perpendicular cliffs 200 feet high in places."

A brief inspection of this striking, well-known landmark (figure 4) in the broad Fort Rock Valley shows that it is an isolated erosional remnant of what was once a much larger tuff ring. The yellowish and brown tuffs with a variety of dark to light colored volcanic fragments are similar to the explosion tuffs at Big Hole.

A detailed study of the attitudes of the tuff layers would probably show whether or not the eroded central part of Fort Rock is actually the crater from which the tuff has been ejected. In general, the thin layers of airborne tuffs dip to the southeast and this would seem to put the center of volcanism to the northwest outside the present confines of Fort Rock. Similar layered explosion tuffs are known to occur beneath the soil zone a mile to the north.

The unusual shape of Fort Rock does not seem to be the direct result of its original volcanic form; rather it is more likely the result of later erosion by wave action in a large pluvial lake, as shown by terraces cut into the southern end of the horseshoe-shaped walls. Hole-in-the-Ground and Big Hole, on the other hand, were unaffected by wave erosion as they lay at an elevation above the level of the lake.

Moffit Butte

Moffit Butte is a bold erosional feature just to the north of State Highway 31 in sec. 7, T. 24 S., R. 11 E., about 10 miles southeast of Lapine. The steep cliffs and badlands type of erosional landforms can be seen from the highway.

The cluster of ridges and hills that makes up the butte appears to be composed of the remnants of one or more tuff rings. Thin to thick layers of yellowish to brown lithic explosion tuffs and tuff breccias occur in a roughly circular to elliptical pattern with the dips of the beds or layers toward the center. There is enough variation in the attitudes at different places so that this may be a cluster of tuff rings superimposed on one another.

Near the highway at the southern edge of the butte there is a small area capped by a thin, cindery, reddish-block basalt flow. A narrow dike or pipe-like mass that is probably the source of the flow cuts the tuffs nearby.

Ridge 28

This unnamed northeast-trending, low ridge in sec. 28, T. 24 S., R. 11 E., is also made up of yellow-brown lithic explosion tuffs that dip to the northwest, south, and southeast. This landform is also believed to be only an erosional remnant of a once larger tuff ring.

Flat Top

The eroded edges of the layered explosion tuffs are present as far north as Flat Top in secs. 13 and 14, T. 24 S., R. 14 E. Here again the lithic explosion tuffs have variable attitudes. Unlike most of the other features described, this one is capped by a thin flow of basalt. This basalt probably filled a shallow broad crater soon after the explosive phase that was responsible for the layered tuffs and overflowed to the northwest. This basalt and the eroded tuffs are surrounded by Recent younger vesicular basalt flows in which original flow features like pressure ridges, lava tubes, and ropy crusts can still be seen.

Niggers Heel and Toe Butte (Cow Cave, Fort Rock Cave)

This small butte about 1½ miles west of Fort Rock is famous as the cave where some of the oldest Indian artifacts from Oregon were found. Sandals woven from shredded sagebrush bark were discovered beneath a layer of pumice that had exploded from Newberry Crater. Dating by the carbon-14 method shows that the sandals were made at least 9000 years ago.

The butte is made up of a variety of pyroclastic and flow rocks. The western part in which the cave (known locally as the Cow Cave) occurs is made up of reddish scoria fragments that are rather loosely cemented. The eastern part of the butte is capped by a thick reddish to black basalt flow that forms a steep cliff with large blocks at its base.

The waves from the large lake that once occupied Fort Rock Valley eroded the cave in the loosely cemented scoriaceous material of this butte, at the same time cutting the terraces at Fort Rock.

Summary

Hole-in-the-Ground remains a unique topographic feature of Oregon for its marked similarity to a meteorite crater, though its origin is volcanic. The meteorite crater of Arizona was produced by the explosion of an iron meteorite, estimated to have weighed between 20,000 and 60,000 tons, upon impact with the earth. The release of the colossal kinetic energy of a body this size, travelling at an estimated speed of around 10 miles per second at impact, blasted out the crater. For Hole-in-the-Ground the energy came from hotmagma making contact with water or water-bearing rock, forming suddenly enormous steam and gas pressure which punched its way through the overlying rock to the surface in one or two bursts. The explosive energy needed to produce a crater this size with a buried nuclear charge would be over 5,000,000 tons, TNT equivalent, on the basis of a similar estimate for the Arizona meteorite crater. Thus can be realized the tremendous energy contained in volcanic forces that produced the Hole-in-the-Ground and the other volcanic explosion features described previously.

The volcanism producing the landforms described in this article was but a small part of the activity going on in the region to the north at Newberry Crater and to the west in the High Cascades during the Pleistocene and Recent epochs. Much of this volcanism was the relatively quiet outpouring of fluid lavas, yet at the same time explosive activity ejected gigantic amounts of pyroclastics. The pumice falls of Mt. Mazama (Crater Lake) and Newberry Crater bear witness of this as two examples in Recent time alone.

Further study of this area will probably reveal more of these tuff cones or their eroded remnants. Doubtless others remain hidden, having been covered by later volcanic flows and lake sediments.

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RECENT VOLCANISM BETWEEN THREE FINGERED JACK AND NORTH SISTER OREGON CASCADE RANGE

Part I: History of Volcanic Activity*

By Edward M. Taylor**

Introduction

On the crest of the Oregon Cascade Range, between the Pleistocene volcanoes known as Three Fingered Jack and North Sister, an impressive array of cinder cones stands in the midst of Recent basaltic lava fields whose total area exceeds 85 square miles (fig. 1). Although each major field is closely approached by a highway, several lava flows and many cones, vents, and other volcanic features have not been described in print. In this paper, the history of each eruptive center first will be interpreted from the standpoint of field observations, and then will be reviewed in an integrated outline of recent volcanism. The volcanic history and geologic maps presented here have been abstracted from a general survey of petrology in the High Cascades of Oregon which the writer has followed for several years and which has progressed from Bachelor Butte to Three Fingered Jack.

North and south geographic limits of the present study are placed along straight east-west lines through Three Fingered Jack and North Sister, respectively; east and west boundaries are drawn coincident with the east and west borders of the High Cascades as outlined by Williams (1957). The temporal range of geologic events extends from the end of the last major glacial episode to the present. It is believed that all exposed eruptive units within these boundaries of space and time are included in this report. Several unofficial, but suitable, geographic names are introduced where reasonable discussion demands them. For background information, the reader is referred to the appended Glossary of Selected Terms and to Williams (1944).

Cones and Flows of Questionable Recent Age

The maps presented in this paper differ slightly from earlier reconnaissance geologic maps (Williams, 1944, 1957) in their definition of Recent basaltic cones and flows. Discrepancies arise with respect to: (1) identification of landforms, (2) recognition of cones and flows which have been glaciated, and (3) recognition of possible pre-Recent cones and flows which have not been glaciated. Included in the first group are the following land forms not previously identified: a glaciated dome of rhyolite and obsidian at the southeast base of Condon Butte, a knob of glaciated bedrock near the terminus of the northwest lava flow from Collier Cone, a nearly flat glaciated

* Part II, Petrographic studies and chemical analyses, to be published at later date.
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surface between Collier and Four-in-One lavas, two glaciated steptoes which rise through Little Belknap lava near McKenzie Pass, a glaciated hill $1\frac{1}{2}$ miles northwest of Yapoah Cone, and a glaciated steptoe at the west end of the Belknap lava field. Landforms of the second group are located on figure 1 by the symbol "X". The third group includes four lava flows which do not appear on the older maps, Scott Mountain, Two Butte, a feature known as the "Cinder Pit," and two cinder cones on the northeast slope of Black Crater. This group is described as follows:

Lava flows, so old that deep forests now hide them from view, issued from four separate vents close to the western boundary of the High Cascades. Their individual histories are relatively unknown. Included here are the Park Creek flow, the flows on the west slope of Maxwell Butte, and the Anderson Creek flow (fig. 1). No cinder cones have been recognized in association with these lavas.

The Park Creek flow is composed of blocks which have been somewhat rounded by weathering. Crustal features and the outlines of lava tongues can be seen only where ancient fires have limited the forest cover. The flow originated near a small hill at the north lava margin, moved south for two miles, and forced Park Creek to undercut a high cliff of sedimentary rocks.

Equally vague is the eruptive history of flow rocks on the side of Maxwell Butte. Two source vents approximately 2.3 miles west of the Maxwell summit are indicated by the distribution of lava, but neither has been located precisely nor has it been possible to trace contacts between flow units. Here too, old forest fires have exposed slaggy crusts and numerous pressure ridges. Where the North Santiam Highway cuts through the flows, their thin, vesicular character can be seen in cross section. Farther west, about two miles from their source, they are found adjacent to the Park Creek flow; relative age has not been determined.

To trace the Anderson Creek flow one must learn to "feel" it beneath the forest floor; indeed, the very existence of fresh lava would be difficult to prove if logging operations had not disclosed striking examples of lava levees and vesicular flow tops. The advanced age of this flow is inferred from the condition of its forest cover in comparison with the cover found on other flows which lie at similar elevations to the north and south. Lava issued from a subdued spur 2.3 miles west of Scott Mountain summit and poured as a cascade into the valley of Anderson Creek. A north lobe appears to have advanced, then stagnated, three miles from the source. Another lobe was channeled west by an intervening hill, and then was deflected northward, where it lies in contact with the northernmost lobe. This western lobe eventually spread into the valley of Olallie Creek. Its terminal lava front, six miles from the source, can be seen beside the Clear Lake Highway.

Scott Mountain is a glaciated shield volcano, located southwest of the Belknap lava field (fig. 1). Upon the summit of Scott Mountain is a small cinder cone of recent appearance. Layered deposits of ash and scoria are abundant near the top, where only an indistinct remnant of the crater rim has survived erosion. The flanks are composed of coarse red scoria and perfectly shaped spindle bombs. Black lava spread over the west and southwest lip of the crater but did not move beyond the cone.

Two Butte is a double cinder cone located 3.4 miles south of Scott Mountain (fig. 1). The cones are 400 feet high, are aligned north-south, and have lost their craters by erosion. Red scoria and spatter are exposed near their summits, but their flanks are mantled in dense forest. Except to the south, where small flows can be traced to the edge of the Lost Creek glacial trough, surrounding terrain bears the

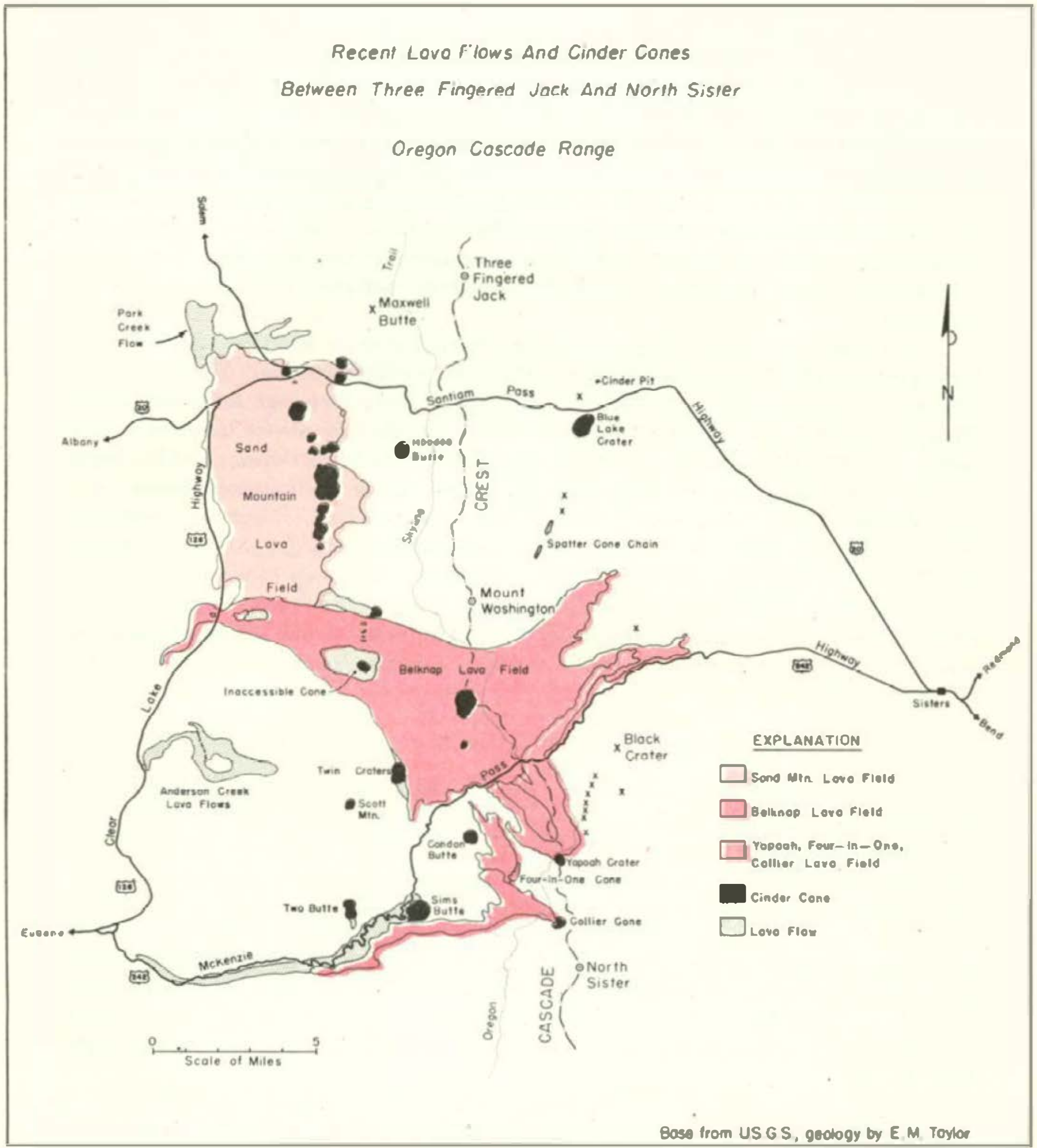


FIGURE I. INDEX MAP

imprint of profound glaciation.

One and one-half miles north of Blue Lake Crater (fig. 1), a diminutive cinder cone has been excavated for road metal. As a result, the conduit - now occupied by a plug of basalt - has been laid bare within a shallow, cinder-covered pit. The designation "Cinder Pit," which appears on the Three Fingered Jack topographic map (U.S. Geological Survey, 1959, 15-minute), will be adopted here. A narrow stream of lava moved only a few hundred feet east from the conduit. The lava rests upon glacial deposits which, as exposed in the pit, have been oxidized by volcanic emanations.

Two other cinder cones with well-preserved summit craters stand 250 and 350 feet above the north and northeast flanks of Black Crater. No glacial deposits nor striae occur upon these cones, but the coarse, weathered scoria on their slopes strongly resembles ejecta from other cones north and south of Black Crater which have been glaciated.

A Recent age for the above cones and flows is open to question, even though they rest upon older glaciated bedrock surfaces or glacial deposits. The last (latest Wisconsin?) major advance of glacial ice between Three Fingered Jack and North Sister is recorded by a variety of features which include lateral and terminal moraines, bedrock striations, vegetation patterns, and glacially transported erratic lithologies. Glaciers, as interpreted from these records, did not cover the Anderson Creek nor west Maxwell lavas during Late Wisconsin time, but may have obliterated their source cones. It is clear that such glaciers reached neither the Park Creek flow nor the Cinder Pit. Similarly, glaciers did not affect Two Butte, but they might have destroyed Two Butte lavas in the adjacent glacial trough. Glacial ice, as outlined by morainal patterns, probably moved between the two cones on Black Crater without disrupting them, and might not have significantly eroded the Scott Mountain cone because of its high-standing position.

Volcanic History of the Sand Mountain Lava Field

Within the High Cascades there are many examples of volcanic mountains arranged in nearly perfect linear or arcuate patterns. Few are as easily recognized as the chain of 22 cinder cones and 41 distinct vents referred to here as the Sand Mountain alignment (fig. 2). An elongate zone of weakness probably developed in the rocks beneath the cones along which magmatic gases and liquids were conducted from the depths to the surface. In detail, this zone diverges northward into two distinct branches. Sand Mountain Cones are the largest volcanoes on the alignment and rise above the intersection of the branches. The principal landforms are geographically as follows: Little Nash Crater and the Lost Lake Group on the north, Nash Crater and the Central Group farther south, Sand Mountain Cones, and the South Group (see fig. 2).

Over a long span of time, the numerous and closely spaced eruptive centers of the Sand Mountain alignment discharged about three-quarters of a cubic mile of lava and a large but unknown volume of ash. The result was an intricate accumulation of overlapping cones, flows, and sheets of ejecta, whose volcanic history is set forth in approximate chronological sequence below.

The oldest volcano exposed on the alignment probably is a small, 150-foot cinder cone located between Nash Crater and the junction of North and South Santiam Highways. Erosion has destroyed all trace of a summit crater, and the lower forested slopes are covered with ash from younger cones. Another denuded cinder cone, approximately 400 feet high, lies one mile southwest of Lost Lake, and has retained only a vestige of its crater rim. Any lava which may have issued from these cones is now lost to view beneath younger flows from later vents.

The Central Group is a tight cluster of five cinder cones, three of which overlap to form an east-west volcanic ridge, half a mile long and 200 feet high. The west end of the ridge contains a small symmetrical crater, but the east end has been breached at its northern base by a great outpouring of lava. The central part of the ridge is occupied by two craters, one nested within the other. Lava issued also from the west base of the ridge, undermining a small satellite cone. In the lava field a short distance west and northwest stand two 100-foot cones with well-preserved craters. Two additional cones at the northwest base of North Sand Mountain strongly resemble those of the Central Group. One is 200 feet high and breached on the west; the other is only 50 feet high but contains a small summit crater.

Lava from the Central Group spread widely to the west, northwest, and north. Much of the west lava now is covered by a younger flow from Nash Crater. To the north, however, lavas poured from the Central Group onto the floor of a broad, glaciated valley, moved over the region now occupied by Santiam Junction, and probably reached the ancestral upper McKenzie River. Several long, isolated ridges and gutters are seen in these lavas just south of the junction, where they trend westward and pass beneath a flow from Little Nash Crater. The ridges often are capped by lava crust, and their sides have been vertically striated by the foundering of adjacent blocks. These features are evidence that the Santiam Junction area was at one time a lake of lava which drained out to the west, probably from beneath a congealed crust.

A short alignment of four cinder cones forms a great ridge across the glaciated valley of Lost Lake Creek, two miles east of Santiam Junction. The lava-dammed lake nearby gives to these cones the collective name "Lost Lake Group." The smallest cone lies against the north valley wall, 700 feet above the lake. On the south, it overlaps the rim of a lower, but much larger cone. Consequently, both cones share a common rim which separates an elongate, shallow crater on the north from a symmetrical, deep crater on the south. A low saddle lies between these northern cones and a centrally located third cone on which there remains only an indistinct crater. The rim of the southernmost cone rises 320 feet above the adjacent Santiam Highway, though the bottom of its crater extends to highway level.

Lava issued from the east base of the north cone and spread eastward, as did a much larger flow from the saddle. Irregular slabs of jagged crust can be seen protruding through a thick overburden of ash along the west shore of Lost Lake. Lava from the saddle also moved west as far as Santiam Junction, where it is deeply buried beneath ash from Little Nash crater, and therefore is exposed best in road cuts.

A large volume of lava was discharged from the base of the north Sand Mountain cone, building a broad ridge which extended 2,000 feet to the west. The ridge was capped by a lava gutter whose walls were breached at frequent intervals. A collapsed lava tube descends the western extremity of the ridge. This lava, which moved far to the west, may be seen on the north shore of Clear Lake. The northern contact with Central Group lava is obscured by ash deposits, but the southern limit of exposure is traced easily against a younger flow from a vent southwest of Sand Mountain.

The South Group consists of four principal cinder cones, all of which probably were associated with extensive lavas, now buried beneath younger flows. The northernmost cone is 1,000 feet south of Sand Mountain, rises 300 feet in height, and contains a deep crater. Next south is a smaller cinder cone which was built adjacent to an elongate southwest-trending ridge of spatter and bombs. Lava issued from the west base of this cone. The largest cinder cone of the south group stands south of the spatter ridge and is 400 feet high. A large central crater is attended by a smaller counterpart on the north flank of the cone, and by a great bocca near the southwest base. Lava from the bocca spread south, surrounding a small breached cone, and southwest to form an extensive flow. The McKenzie River pours over this lava at Koosah Falls. The lava is obscured on the south by flows from Belknap Crater; to the east and north the lava is overlain by later flows from Sand Mountain.

Nash Crater is a cinder cone which was built 500 feet above a lateral moraine. The summit contains a north-south trench-like crater 1,000 feet long with a smaller symmetrical crater set into its west rim. A narrow ridge of spatter extends from the south base of Nash Crater, and is surmounted by six vertical conduits which range from 30 to 5 feet in diameter and from 40 to 30 feet in depth. These conduits lead to a lava tube which has collapsed at the south end of the ridge. Lava from this vent moved west, damming Hackleman Creek to form Fish Lake, and for this reason is called the <u>Fish Lake Flow</u>.

At the northwest base of Nash Crater is a broad depression rimmed with spatter. Approximately 100 feet northwest, a 5-foot spatter cone surrounds a vertical conduit which is 25 feet deep. Both vents probably lie above a lava tube and mark the source of the extensive flow now crossed by South Santiam Highway. Sawyer's Cave, adjacent to the highway, is a lava tube far removed from the source of the flow. Lava from the northwest vent of Nash Crater dammed the ancestral McKenzie River (now called Park and Crescent Creeks) to form a swampy area known as Lava Lake. At this point, the flow turned abruptly southward, following the McKenzie drainage to Fish Lake. The <u>Lava Lake Flow</u> rests upon lava from the Central Group and is overlain by a flow from Little Nash Crater.

The most extensive lava flow exposed on the Sand Mountain alignment (referred to here as the <u>Clear Lake Flow</u>) was fed from a vent located half a mile southwest of Sand Mountain Cones, and dammed the lake for which it is named. A circular pit, 50 feet in diameter, displays several flow units in its walls and probably represents a collapse depression over the lava source. A smaller pit, 200 feet to the east, separates the collapse depression from an east-west spatter ridge 600 feet long. The west end of the ridge contains a shallow crater 30 feet in diameter. On the summit of the ridge are two vertical pipes, 3 and 6 feet in diameter, which are at least 40 feet deep. Lava from the collapse depression spread west to the McKenzie River, forming a dam from Sahalie Falls to Clear Lake. The upright trees which may be seen in the depths of the lake are well known. Wood from one of the submerged trees, drowned as the lake rose behind its lava dam, has been given a radiocarbon age of approximately 2,950 years B.P. (Benson, 1965), thus fixing the date of the eruption of the Clear Lake Flow at about 1,000 B.C.

The south flank of Sand Mountain is interrupted by a broad furrow which, at its base, leads to a bocca and a lava gutter. Lava from this vent moved chiefly eastward and then four miles to the south, where it now lies buried beneath younger flows from Belknap Crater. It should be noted that, although eruptions from the southwest

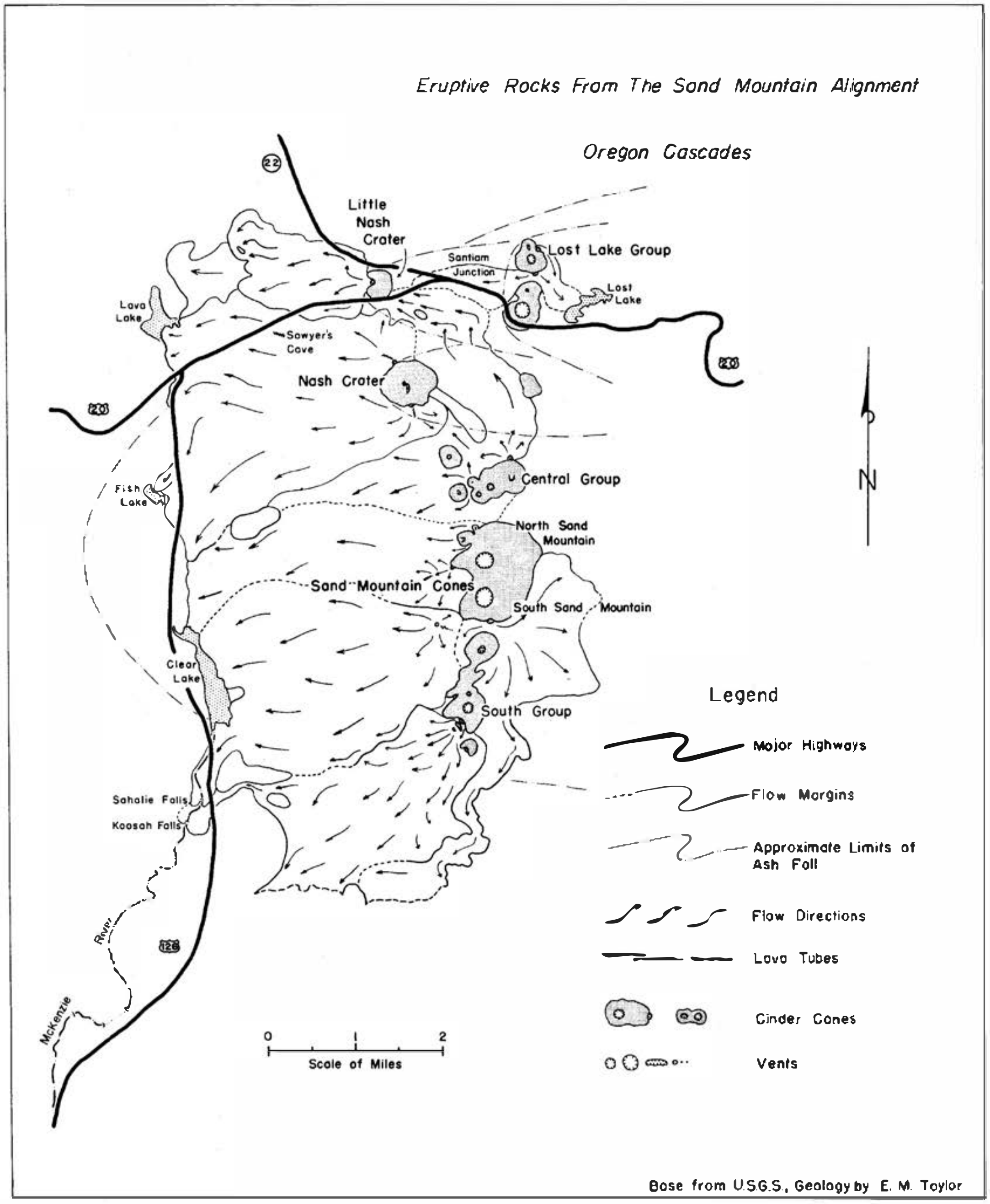

Eruptive Rocks From The Sand Mountain Alignment
Oregon Cascades
22
Little Nash Crater
Santiam Junction
Lost Lake Group
Lost Lake
Lava Lake
Sawyer's Cave
Nash Crater
20
20
Central Group
Fish Lake
North Sand Mountain
Sand Mountain Cones
South Sand Mountain
Clear Lake
South Group
Sahalie Falls
Koosah Falls
River
McKenzie
126
N
Legend
Major Highways
Flow Margins
Approximate Limits of Ash Fall
Flow Directions
Lava Tubes
Cinder Cones
Vents
0
1
2
Scale of Miles
Base from U.S.G.S., Geology by E. M. Taylor

FIGURE 2.

and south Sand Mountain vents probably occurred at about the same time, their common lava boundaries are obscured by ash deposits and their relative age is unknown. Consequently, the age of Clear Lake does not necessarily define a maximum age for Belknap lava.

Lavas from the cinder cone called Little Nash Crater probably are the youngest eruptive rocks on the Sand Mountain alignment. The cone has been quarried, exposing a complex internal stratification. A persistent structural discontinuity may be seen in the quarry faces, which suggests that the process of cone building was interrupted briefly by violent explosions which greatly enlarged the crater.

Road cuts north of the cone display weathered till overlain by a three-inch layer of fine black ash, which is attributed to eruptions from Nash Crater. Resting upon the ash layer is a 4- to 5-foot bed of coarse ejecta from Little Nash Crater. The lower part of this bed contains abundant accidental fragments derived from glacial deposits beneath the cone. Late in its history, Little Nash Crater was breached on the west by a flow whose volume is approximately nine million cubic yards.

Some cones of the Sand Mountain alignment, such as Little Nash Crater, were constructed and ceased to emit ash before a significant amount of lava appeared; others, such as Nash Crater and the Sand Mountain Cones, ejected ash throughout the course of lava extravasation. It is a significant fact that as one crosses westward over the lava field from Sand Mountain Cones (which were the greatest producers of ash), the average thickness of ash cover increases because older lava surfaces are encountered and more of the total ash fall is exposed. Most of the ash from Sand Mountain Cones drifted east and northeast, heavily blanketing an area of more than 100 square miles. This material has been so extensively reworked by surface water that it is difficult to reconstruct an original thickness distribution.

The modern appearance of Sand Mountain Cones is one of surprising freshness and perfection in view of the fact that most of the ash was expelled more than 3,500 years ago (see discussion of Blue Lake Crater). Some ejecta fell upon the 3,000-year-old Clear Lake flow, and it is possible that still later eruptions contributed to the form of the cones.

Eruptive Rocks from Inacessible Alignment and Twin Craters

Three and one-half miles southwest of Mount Washington, a short alignment of four cinder cones has been nearly buried by Belknap flows (fig. 1). The southernmost and largest cone, here named Inaccessible Cone, now lies five miles from the nearest road and is surrounded by a wide barrier of jagged lava. The cone contains a symmetrical crater and is encircled by flows which issued from numerous boccas at its base. The Belknap flows partly obscure three smaller cones which lie one mile to the north. An unnamed cone, offset near the north end of the Inaccessible alignment, is 300 feet high and has been breached on the west and southwest by a flow of gray basalt, charged with bombs. The flow has been traced westward beneath the Sand Mountain and Belknap lava fields, and thus is older than both of them. In outward appearance, the lava from this cone closely resembles the glaciated and nearly ubiquitous, pale gray bedrock which is so abundant in older parts of the High Cascades. It is probable that additional vents and a small field of lava associated with the alignment have been lost to view.

Twin Craters is a cinder cone located at the margin of the Belknap field, three miles southwest of the Belknap summit (fig. 1). The cone is 300 feet high and the north and south craters are about 200 feet deep. A small pit, 30 feet in diameter, is set into the east rim of the north crater. The final ejecta from the north vent consisted of fine scoria and ash which accumulated in stratified deposits on the crater rim. The south crater emitted clots of spatter which, as they fell upon the rim, split apart and disgorged tiny streams of lava. Scoria and bombs litter the glaciated landscape to the west. North of the cone, several mounds of red cinders are imperfectly exposed along the margin of Belknap lava; whether they represent separate cones or scoria-covered flow ridges is not known. Boccas exist on all sides of the Twin Craters cone, but most of them are clustered upon the north and south flanks. Lava from these vents must have been very fluid, for some flows are only three feet thick and their upper surface is coated with minute, glassy spines. An extensive lava field may have spread into the broad glaciated valley which then existed to the north; if so, it is deeply buried beneath the Belknap volcano.

Hoodoo Butte

Hoodoo Butte is an isolated cinder cone which rises 500 feet above the eastern edge of a glaciated platform, midway between Sand Mountain Cones and Santiam Pass (fig. 1). The small summit crater is open to the east, but could not have been breached by lava because none has been found in association with this cone. Instead, the incomplete appearance of the crater rim is a result of the very irregular topography on which the cone was built; much of the ejecta simply fell over the east edge of the platform. Although Hoodoo Butte stood in the path of fallout from Sand Mountain Cones, most of this ash has been washed onto the surrounding lowlands. A thick deposit of Sand Mountain ash still survives on the crater floor.

History of the Belknap Volcano

Of the volcanic centers discussed in this paper, none poured forth a greater volume of lava than the shield volcano which is surmounted by Belknap Crater, Little Belknap, and related vents (fig. 3). Williams (1944) has provided a lucid description of the Belknap shield; only its salient features are outlined here. The surface of the mountain is covered largely by lava which poured repeatedly from vents marginal to a composite summit cone. This lava was relatively fluid and eventually inundated an area of more than 37 square miles. It did not move in long, continuous streams. Instead, short channels branched and crossed one another, resulting in thin lobes with complex drainage patterns. Accurate reconstruction of the surface on which the volcano rests is precluded by the great thickness and widespread distribution of lava. Consequently, 1 1/3 cubic miles is regarded as only a rough estimate of the volume of Belknap rocks.

The oldest exposed lavas of the Belknap shield occur on its eastern flanks. They were erupted from vents now poorly defined, which may have been subsequently buried as the summit cone reached final development. These lavas moved principally northeastward, diverging into two lobes on either side of a ridge called Dugout Butte. Both lobes descended to an elevation of 4,150 feet, seven miles from their source.

The summit cone of the Belknap volcano rises 400 feet above its basal shield. Two deep craters at the top of the cone emitted ashes and coarse cinders, which accumulated as high mounds of stratified lapilli-tuff on their east rims. In the walls of

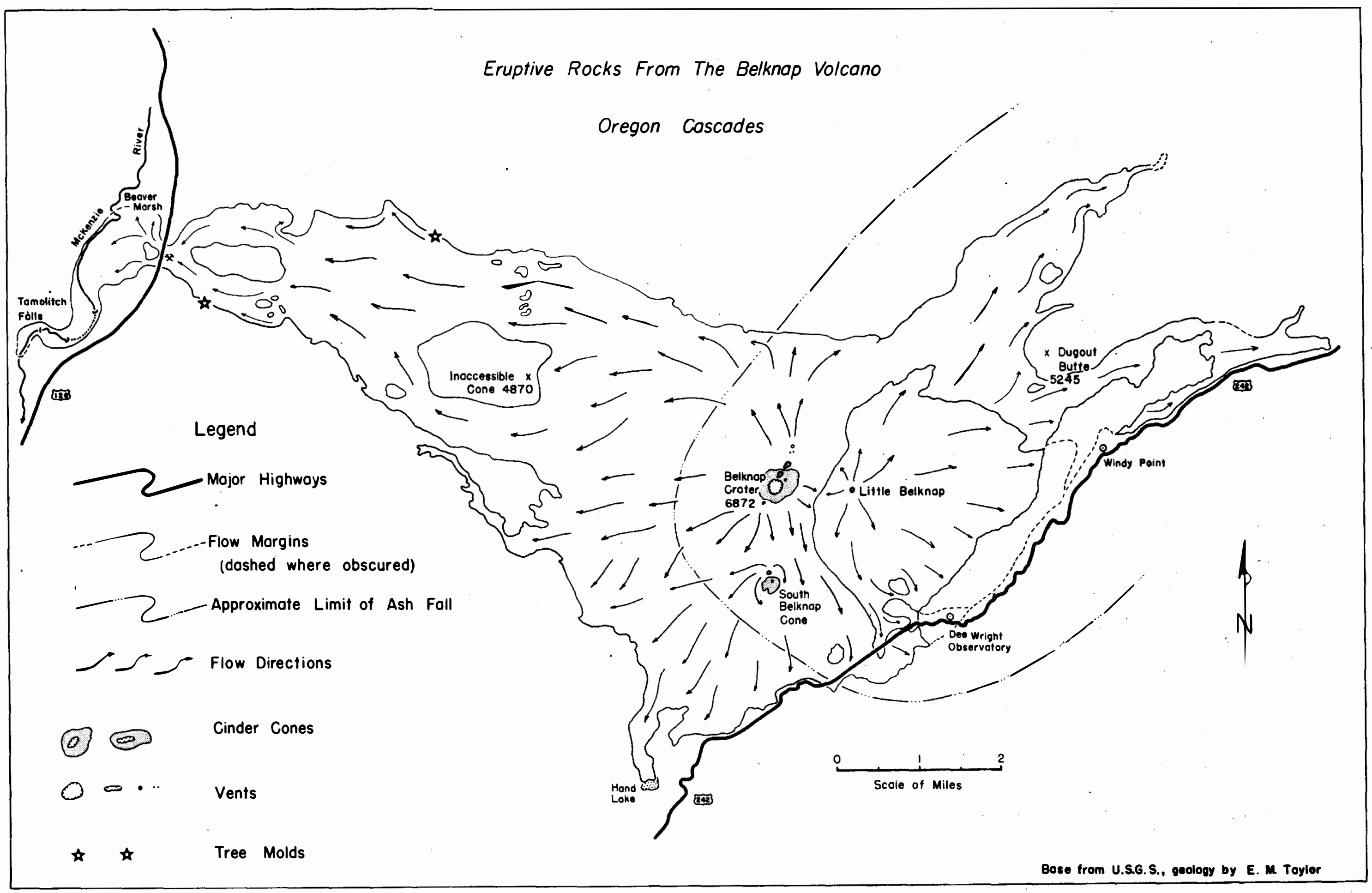

Eruptive Rocks From The Belknap Volcano
Oregon Cascades
Mckenzie River
Beaver Marsh
Tamolitch Falls
126
Inaccessible x Cone 4870
Belknap Crater 6872
Little Belknap
South Belknap Cone
x Dugout Butte 5245
Windy Point
Dee Wright Observatory
242
Hand Lake
0 1 2
Scale of Miles
N
Legend
Major Highways
Flow Margins (dashed where obscured)
Approximate Limit of Ash Fall
Flow Directions
Cinder Cones
Vents
Tree Molds
Base from U.S.G.S., geology by E. M. Taylor

FIGURE 3.

the southern crater, which is about 250 feet deep and more than 1,000 feet wide at the rim, thick flow rocks are exposed. Some lava poured over the southwest lip of this crater and is now partly obscured by spatter. Well-formed spindle bombs, up to three feet in length, are common along the west rim of the north crater. A broad pit 200 feet long was blasted through a bocca at the north base of the cone. Two small spatter cones appeared at a late stage about 1,000 feet still farther north.

The distribution of ash and cinders on the rim of Belknap Crater, as described above, was caused by strong and prevailing wind transport to the east. Thin deposits of scoria are found on lava immediately west of the cone, but as the eastern slopes are approached the lavas become mantled in black ashes and fine cinders. A wide area from Dry Creek on the north to Black Crater on the south was heavily blanketed. Deposits have been recognized eight miles to the east.

During a late stage in the development of the Belknap summit cone, vast quantities of lava issued from boccas on the south, west, and north and poured west toward the McKenzie River. Ropy surfaces and lava squeeze-ups between large rafted platforms of broken crust are common here. Lava from the south vent poured across older lava from Twin Craters; three miles from the Belknap summit, the western streams overran lava and cinder cones of the Inaccessible alignment. Farther west, the Belknap lavas poured over flows from the south vent of Sand Mountain and from the south group of the Sand Mountain alignment, before finally plunging in a steep cascade into the McKenzie Canyon.

The McKenzie River was altered profoundly by the lava which spread across its path. A broad, swampy area known as Beaver Marsh formed upstream from the point where the river now flows onto the Belknap rocks. Where it once flowed freely through its open canyon, the river is now gradually absorbed into the buried talus along the canyon margins and into permeable zones between lava units, reappearing at Tamolitch Falls. Downstream from the falls, the flow has been reduced by erosion to a lateral terrace, perched on the west canyon wall 30 feet above the level of the river.

Tree molds were formed along the margins of the west Belknap flows. They are displayed best at the westernmost locality shown in Figure 3. Here, several dozen molds range from 1 to 5 feet in diameter and from 6 to 15 feet in depth. Most of them are vertical and widen downward. Hemicylindrical trenches as much as 35 feet long occur where trees fell onto the pasty lava. In most areas tree molds are rare because lava must be sufficiently fluid to conform to the shape of a tree, yet must not flow or be deformed after the tree has been consumed. In the present instance, the Belknap flow spilled into a protected recession in a steep, north-facing slope which presumably was, at the time of the eruption, as moist and deeply forested as it is today. The level surface of the resulting pond is an indication of the fluidity of the lava at the time of its isolation from the active stream. From the buried soil at the base of one of the molds, the writer excavated a radial system of large roots which had been deeply charred. Radiocarbon analysis of this material indicates that trees were burned by the west Belknap flows about A.D. 360 ± 160 years (WSU-292). This date is based upon a C-14 half-life of 5,570 years.

One mile south of the Belknap summit is a small volcano referred to here as the South Belknap Cone. This cone was breached on the southwest by lavas which then spread over the south base of the Belknap shield. A later flow, from a vent 300 feet to the northwest, surrounded the cone and inundated the early lavas. The later flow overlapped the west Belknap lava and, at its farthest extension, poured south through a narrow gap into Lake Valley, where it now forms the north shore of Hand Lake.

The latest addition to the Belknap volcano took the form of quiet discharge of lava from a vent called Little Belknap, one mile east of the summit craters. So much lava issued from this one point that a subsidiary shield was formed. It is surmounted by a chaotic heap of cinders and blocks from which collapsed lava tubes diverge radially. One of the western tubes can be followed to its confluence with a vertical conduit which is approximately 20 feet in diameter, and which remains choked with snow, even in late summer. Lava from Little Belknap spread east to within one mile of Windy Point and southeast to McKenzie Pass. It rests upon the ash from Belknap Crater and is overlain by younger flows from Yapoah Cone.

A peculiar, and general, feature of the flow rocks from Little Belknap is seen along the Skyline Trail half a mile northwest of the McKenzie Pass Highway, where the lava stream diverged after passing between two prominent steptoes. As it cooled, the contracting surface warped upward to lift part of the crust, together with its still-plastic substratum, and peel it back upon itself. Thick overturned slabs may be found which are as much as 10 feet wide and 50 feet long, usually parallel to the direction of flow. Except for distortion due to contraction and fragmentation, each slab matches perfectly the adjacent counterpart surface from which it was pulled. Such features will be referred to as lava curls.

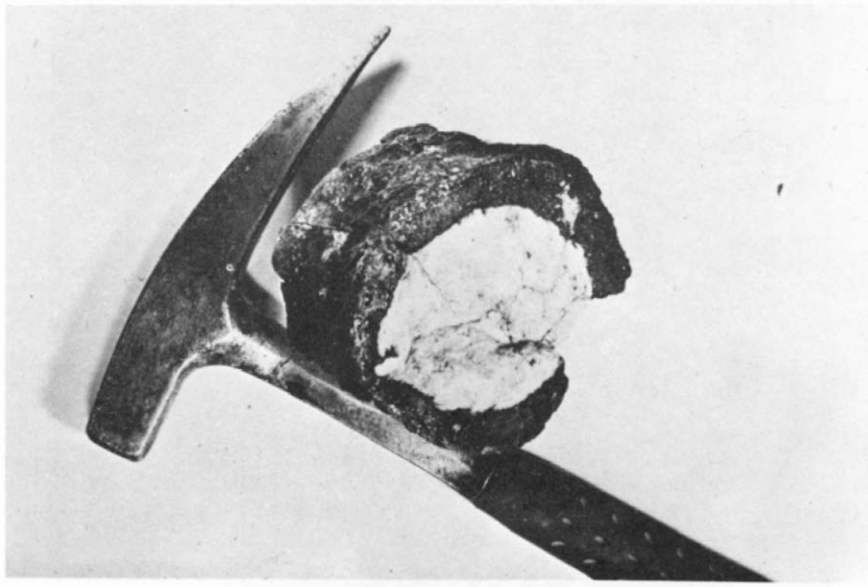
Blue Lake Crater

Blue Lake, as seen from the Santiam Pass Highway, is $3\frac{1}{2}$ miles east of the Cascade crest (fig. 1). It is 0.5 mile long and 0.2 mile wide, and set in a deep pit formed by Recent volcanic explosions of great violence. The Blue Lake eruptions resulted in at least three overlapping craters which are aligned approximately N.25°E., and which fall within a geographic trend common to Belknap Crater and the Spatter Cone Chain to the south, and the "Cinder Pit" to the north. The first (and only?) published suggestion that Blue Lake might occupy a volcanic crater appeared in 1903 (Langille and others).

The southern half of Blue Lake is rimmed by a crescentic ridge which, in places, stands 300 feet above the water and 150 feet above the adjacent topography. The outer slopes are covered with basaltic cinders, bombs (some of which are six feet long), and accidental fragments of older, underlying lavas. Inner slopes of the rim generally lead to cliffs which disappear into azure depths. If one may compare Blue Lake crater to other Cascade craters of similar diameter, the lake is probably in excess of 300 feet deep.

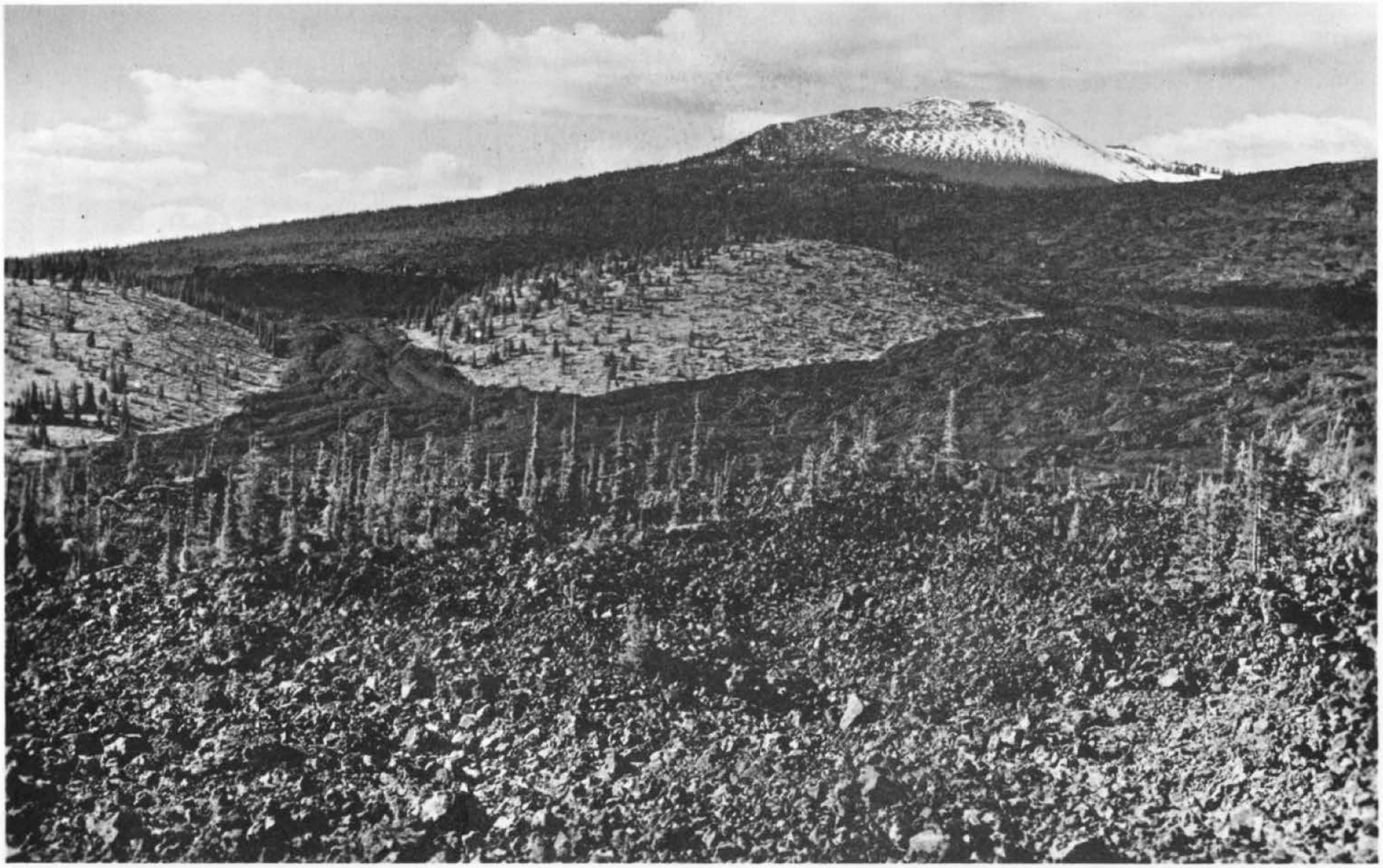
Some of the lakeshore cliffs may have been formed by the collapse of over-steepened crater walls, but no prominent dislocations of a concentric type have been found. The north crater wall, now largely submerged, was blasted through pre-existing bedrock, fragments of which are found scattered over the nearby landscape. Consequently, it appears that Blue Lake crater was the result of upward explosions rather than interior subsidence. Above lake level, the southern crater walls are composed of crudely stratified cinders and bombs with intermixed bedrock blocks. No Recent lava flows have been recognized in the Blue Lake area.

Bombs and blocks were ejected in all directions from the crater, but most of the fine scoria and ashes drifted east and southeast. A typical section taken through these deposits contains, at its base, weathered till overlain by 2 to 3 feet of fine black ash attributed to eruptions of the Sand Mountain alignment. Capping the black ash is a

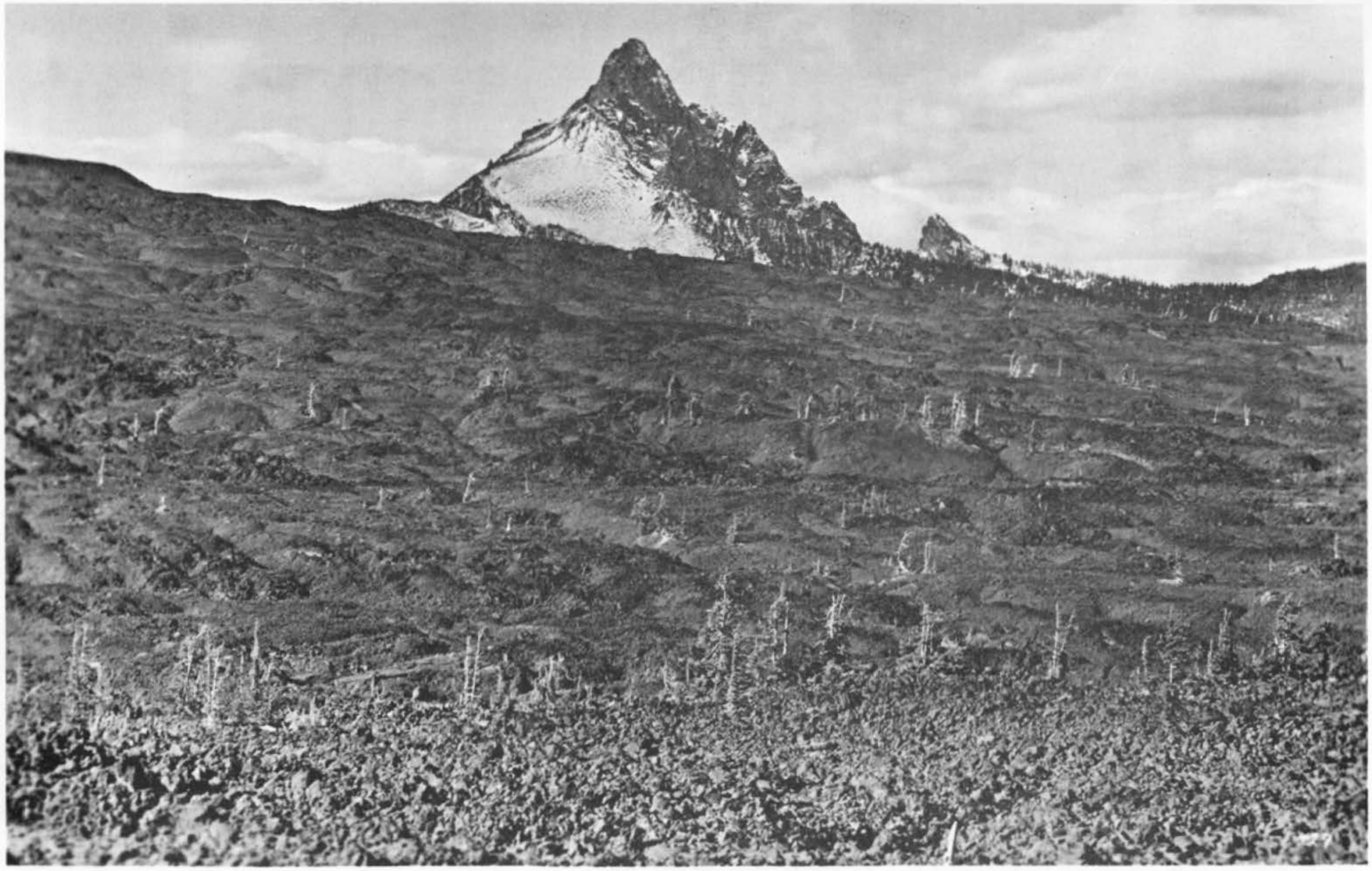


Pumice-cored volanic bomb with basaltic rind from Four-in-One Cone.

Lava gutter west of Collier Cone provides pathway for Skyline Trail.



Belknap Crater seen from Dee Wright Observatory: Belknap Crater (snow-covered skyline) is impressive in stature, but is only a pile of cinders on the summit of a vast shield of recent lava. Forests in background grow upon old Belknap lavas; trees in foreground stand upon young lava from Yopooh Cone. Lava of intermediate age and position surrounds "islands". and issued from a subsidiary vent called Little Belknap. (Oregon State Highway Department Photograph No. 423)



Lava from Little Belknap: Desolate fields of blocky lava (foreground) from Yopoah Cone, and hummocky lava (background) from Little Belknap, lie between Dee Wright Observatory and the volcanic plug of Mount Washington. The jogged features of these lava surfaces were formed less than 1,500 years ago. (Oregon State Highway Department Photograph No. 427)

Lava flows from Collier Cone: Collier Cone (upper left) and lava streams which spread from its crater down the west slope of the Cascade Range (foreground), are probably the most recent manifestation of millions of years of Oregon vulcanism. Left of the cone is the Ahalapam Cinder Field; lava gutters lead west and northwest to lava lobes which are marked by levees and pressure ridges. Large volcanoes behind the cone are North Sister (left) and Middle Sister (right). Collier Glacier (center) has receded from the cone to its present position in only 40 years. In the background are Broken Top (left) and South Sister (right). Four-in-One Cone and lavas are visible at lower left. (Delano Aerial Oblique No. 631234) thick accumulation of scoria which may be traced directly to Blue Lake. Charred wood from the limb of a conifer has been excavated from the sharp interface between the scoria and ash. The radiocarbon age of this material is 3,440 ± 250 years B.P. (WSU-291), assuming a C-14 half-life of 5,570 years. The eruption of Blue Lake Crater commenced therefore, at about 1,500 B.C. This date, when compared with the age of Clear Lake (about 1,000 B.C.), suggests that most of the ash from the Sand Mountain alignment was deposited in the Blue Lake area 500 years before the final eruptions of Sand Mountain lava.

The Spatter Cone Chain

A chain of spatter cones, one mile long, trends N.23°E. across the valley of Cache Creek between Blue Lake Crater and Mount Washington (fig. 1). Volcanic features are restricted to north and south segments, but several trench-like depressions aligned parallel to the midsection of the chain outline a strong subsurface continuity. The northernmost vent is a circular crater, 10 feet deep, which appears to have emitted only gas. About 200 feet south is the first of four spatter cones, with craters 30 to 40 feet deep, which surmount a narrow ridge of spatter and scoria. Still farther south, a series of discontinuous grabens, averaging 10 feet in width and 3 feet in depth, leads to a southern line of vents. Deposits of ejecta occur intermittently along the grabens. Fractured bedrock is exposed where the trend of this chain intersects Cache Creek, but no displacements have been recognized. There are seven southern vents, as follows: Three small craters to the north are separated by a short graben from three large craters located on a spatter ridge to the south; the central crater on this ridge contains a small crater in its north rim. A shallow graben extends about 150 feet south from the ridge. Volcanic rocks of the Spatter Cone Chain overlie ash deposits that are correlative with the deposits of fine ash near Blue Lake Crater.

Sims and Condon Buttes

The western third of McKenzie Pass Highway follows a Recent lava flow, $9\frac{1}{2}$ miles from source to terminus. The source cone is Sims Butte, located $6\frac{1}{2}$ miles south of the Belknap volcano (fig. 1). The cone is 650 feet high and is broadly indented on the west side by a shallow crater, located 400 feet below the summit. Ejecta are coarse and are confined largely about the vent within a circular area of one-mile radius. The limited extent and symmetrical distribution of ejecta suggest that the asymmetry of the cone is a result of lava breaching rather than prevailing wind direction.

Short flows emerged from the north base of the cone, but most of the lava issued from a west bocca, 200 feet below the shallow crater. Collapsed lava tubes may be traced downstream from this bocca for several hundred yards. At one point, where the flows are steeply inclined, a 70-foot lava tube descends beneath the crust. Two "skylights" penetrate the thin roof, and collapse depressions define an inaccessible western continuation of the tube.

The extensive lava flows from Sims Butte spread onto a topographic shelf west of the cone, then poured into the Lost Creek glacial trough. They covered the floor of the trough and moved westward to within a quarter of a mile of Limberlost Forest Camp. White Branch, Obsidian, Linton, and Proxy Creeks all disappear beneath this blanket of lava before reappearing in a series of large springs at the head of Lost

Creek. It has not been possible to trace single flow units from Sims Butte for long distances because of the overlying Collier lavas and the heavy forest cover, and because the Sims lava advanced as thin, overlapping sheets of limited extent. Lava tongues, only one foot thick, cover several acres along some parts of the flow margins. The best cross-sectional exposures of Sims lava are seen along the switchbacks of the McKenzie Pass Highway, where five or more separate flows can be counted in one 15-foot embankment. A typical flow is 3 to 5 feet thick with a thin, dense crust resting upon a base of unconsolidated rubble.

Condon Butte is three miles northeast of Sims Butte and is considered here to be genetically related to it. The cones are about the same size, equally forested, and their ejected material is, for all practical purposes, identical. Condon Butte, however, did not emit a great volume of lava and as a consequence the cone is symmetrical. In the summit are two nested craters from which short, stubby flows moved down the southwest flanks.

Volcanic History of Yapoah Cone and Related Vents

Between McKenzie Pass Highway and the North Sister, the Skyline Trail (fig. 1) leads across an alignment of six cinder cones and gas vents which is 1.4 miles long and trends S. 4° W. At the midpoint of the alignment stands Yapoah Cone, and from its base several lava streams extend northward, covering 6 square miles (fig. 4). Lava from Yapoah Cone rests upon Little Belknap lava and is overlain by ashes and fine scoria from Four-in-One Cone.

Prior to Recent time, an unusual type of flow rock was erupted from a set of fissures along the Cascade crest between Black Crater and North Sister (fig. 1). Bombs and lava were discharged simultaneously and spread down the western slopes in what might be described as an agglutinate flow. A typical unit is 30 feet thick with a 10-foot crust of red bombs and spatter which passes gradationally into an underlying dense lava choked with bombs. Yapoah Cone and related vents, together with Collier Cone and the Ahalapam Cinder Field (fig. 5), rests upon the glaciated agglutinate flow rocks. Some of these Recent and older-than-Recent eruptive features are not easily distinguished along the crest; consequently, an interpretation of the volcanic history of this area may be subject to a wide variety of opinion.

Hodge (1925) named the Ahalapam Cinder Field and described it as "two rows of volcanoes having the appearance of morainal topography." Williams (1944) suggested that "ejecta from Collier and Yapoah cones had accumulated on morainic mounds," but noted the presence of "many large bombs, several more than four feet across and a few even eight feet across, scattered among the fine scoria." The bombs were cited as evidence of eruption from local vents and most of the crest in this area was mapped as a field of Recent eruptive activity (Williams, 1957). In the opinion of the writer, however, the Ahalapam Cinder Field is a mantle of scoria and ash ejected from the Collier vent and deposited upon glacially dissected agglutinate flows. Recent eruptions between McKenzie Pass and North Sister have occurred only adjacent to Scott Pass and along the Four-in-One and Yapoah-Collier alignments, as described below.

Yapoah Cone rises 500 feet above its surroundings except on the south side, where it abuts against a glaciated ridge of agglutinate flows. The summit crater is about 300 feet long in a north-south direction, 100 feet wide, and mantled with red cinders. Stratified deposits of yellow lapilli-tuff occur on the east rim, but outer

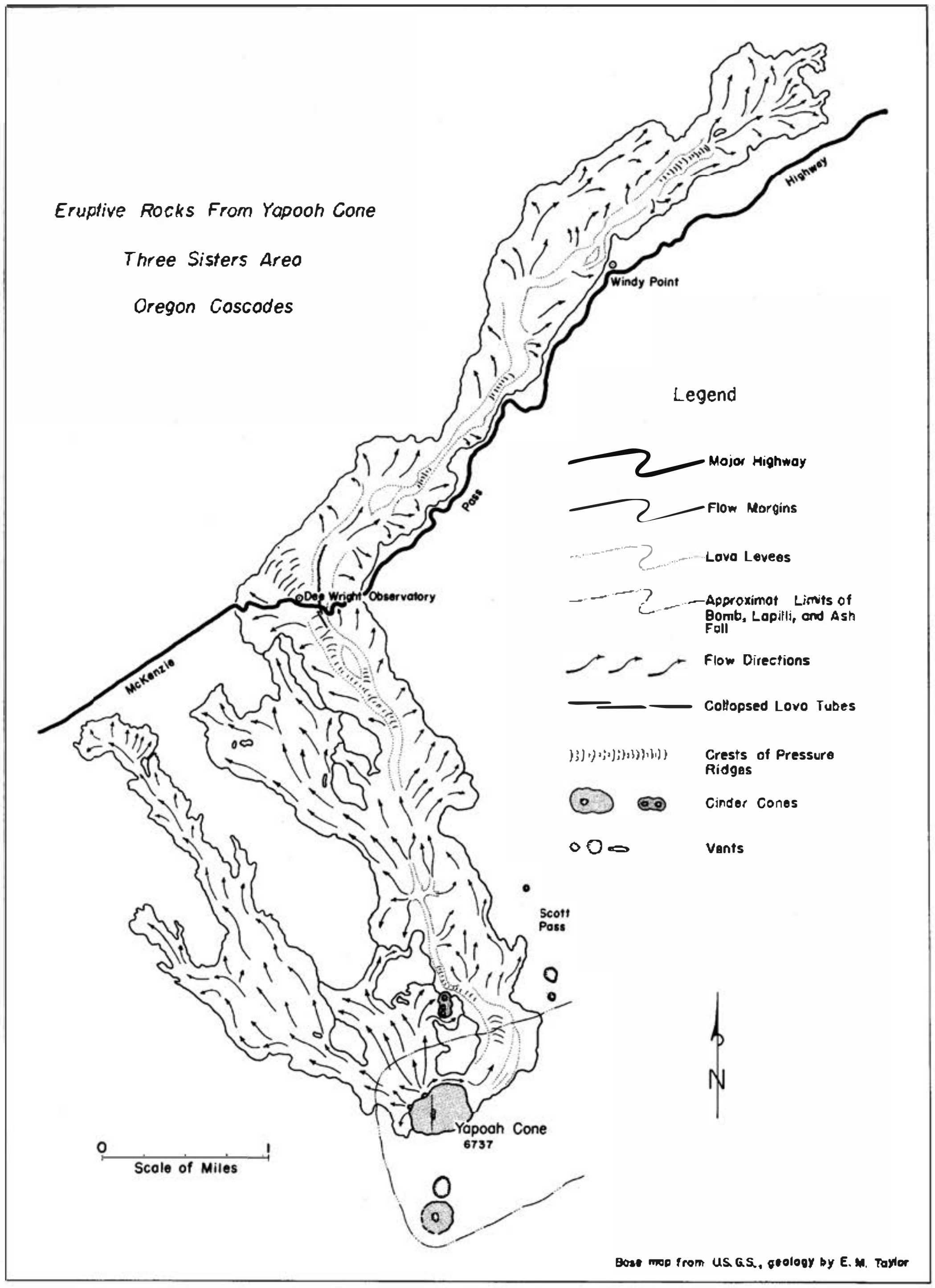

Eruptive Rocks From Yapooh Cone
Three Sisters Area
Oregon Cascades
Highway
Windy Point
Pass
Dee Wright Observatory
McKenzie
Legend
Major Highway
Flow Margins
Lava Levees
Approximat Limits of Bomb, Lapilli, and Ash Fall
Flow Directions
Collapsed Lava Tubes
Crests of Pressure Ridges
Cinder Cones
Vents
Scott Pass
Yapooh Cone
6737
N
0
1
Scale of Miles
Base map from U.S. G.S., geology by E. M. Taylor

FIGURE 4.

slopes of the cone are covered with black cinders. The remarkable symmetry of Yapoah Cone may be due to persistence of explosive activity until a late stage; all lavas adjacent to the cone are partly obscured by ashes and scoria. Pyroclastic deposits resulting from Yapoah eruptions, however, are neither as thick nor as widely distributed as similar material from nearby Collier and Four-in-One Cones.

Half a mile north of Yapoah Cone, a linear cluster of three small spatter cones was nearly engulfed by Yapoah lava. Rocks from these vents are identical to ejecta of the Yapoah type, and probably came into existence during the same eruptive episode.

Other Recent volcanic activity near Yapoah Cone may antedate the Yapoah eruptions. A gas vent was blasted through the agglutinate flows 0.3 mile south of Yapoah Cone, leaving a circular depression 300 feet in diameter (fig. 4). Immediately south of the gas vent a small, asymmetrical cinder cone was built on the margin of a precipitous ridge. The west flank of this cone rises 350 feet above nearby lowlands, while its eastern rim stands only 30 feet above the ridge top. Near Scott Pass, one mile to the northeast, a deep, round pit, 400 feet in diameter, interrupts a glacially striated surface cut on red agglutinate flow rocks. Other poorly defined gas vents exist to the north and south of Scott Pass and are located along the system of agglutinate flow fissures mentioned previously. These vents may be assigned on a provisional basis to a Recent, but pre-Yapoah, eruptive episode. The activity was confined largely to the incipient Yapoah alignment, but also reached the surface through conduits along the older agglutinate flow fissures.

Lava units from Yapoah Cone are composed of porous crustal blocks which become increasingly coherent downward, grading into a thin, dense base. A cross-section of this structure is exposed in highway cuts east of Dee Wright Observatory on McKenzie Pass.

Yapoah lava was discharged first from a bocca on the north, then from a bocca on the northwest side of the cone. The first lobe, here referred to as the Observatory Lobe, was channeled northward until it reached that part of the Cascade crest now traversed by McKenzie Pass Highway. At this point it encountered the Little Belknap shield volcano and was deflected down the east slope of the range, eventually reaching a total length of 8 1/3 miles.

For a distance of $1\frac{1}{2}$ miles downstream from Yapoah Cone the final lavas of the Observatory Lobe moved in a narrow channel perched on the lobe crest, and confined by lava levees. At intervals the levees were breached, releasing dendritic cascades which poured laterally down their flanks. At its terminal end, the channel split into three principal branches. The central and eastern branches fed the main lobe; the west branch produced a subsidiary lobe only two miles long. The remaining length of the Observatory Lobe is surmounted by a system of lava gutters which are, in some places, narrowly confined between lava levees. Upstream from such constrictions, transverse pressure ridges were formed; downstream, the lava frequently drained from beneath a congealed crust. In this way lava tubes were produced and long narrow trenches occur where their ceilings have collapsed. An excellent example of a collapsed tube is to be seen just east of the Dee Wright Observatory on both sides of McKenzie Pass Highway.

A later lobe issued from a bocca approximately 100 feet above the northwest base of Yapoah Cone. Initially, the lava spread northward, plunged down a steep slope, and chilled to a standstill at the head of a large steptoe called "The Island." Succeeding lava flows by-passed this lobe on the west and formed an extensive ribbon which ceased to move only after it had reached the base of the Belknap volcano three miles distant. The northwest bocca now is represented by a gutter leading to an open tube, which descends 20 feet into the flanks of the cone before it pinches out above a fill of jagged lava.

Volcanic History of Four-in-One Cone and Related Vents

A series of 19 visible vents forms a short volcanic alignment about $1\frac{1}{2}$ miles southwest of Yapoah Cone. The northern end of this alignment is marked by an elongate ridge of four coalescing cinder cones, appropriately named Four-in-One (fig.5). At its southern end the alignment was inundated by lavas from Collier Cone. Between Four-in-One Cone and the margin of Collier lava, three small vents can be seen. One is slightly offset to the east and covered with scoria; two others are half-obscured by the Collier lobe, and emitted pasty clots of black spatter and accidental fragments of underlying rocks. In the Collier midstream, the summits of four cinder cones are exposed, each with a well-defined crater. The northern cone of this group was breached on its southwest flank by a lava flow which now is covered by the Collier lobe. Only the source area of the lava and its terminal extremity, one mile to the northwest, are exposed.

The eruptive history of Four-in-One Cone is not known in detail, but several major events can be outlined. Activity developed first along a half-mile fissure, and probably was soon concentrated at four conduits separated by a uniform interval of about 700 feet. Concurrent eruption of bombs and coarse cinders resulted in the construction of four overlapping cones which attained a height of 200 feet. Lava escaped from the southern base of the south cone, covering several acres with a thin veneer of black vitreous rock, crowded with tiny vesicles. During the height of the eruption the cone was enveloped in black spatter, while scoria and ashes, composed chiefly of turbid brown glass, drifted east to the Cascade crest. Near the vents, the resulting deposits are more than 50 feet thick. Southward, they pass beneath Collier lavas; to the north they rest upon flow rocks from Yapoah Cone.

Following the more violent stages of activity, four deep gashes were excavated in the west slope of the cone by streams of lava which eventually covered 1.4 square miles and reached a point 2 3/4 miles to the northwest. Counting from the north vent, the flow from the second was obscured by a subsequent flow from the third, which seems to have issued at about the same time as flows from the first and fourth vents. Because the lavas moved northwest and the ash was blown eastward, they do not in general overlap. The breaching of the cone, however, clearly involved both its reddish core and its black covering of spatter.

Surfaces on Four-in-One lava resemble those found on the Yapoah lobes, except for the prevalence of red scoria (quarried from the cone) and the lack of long, continuous channels bordered by lava levees. The Four-in-One flows tend to branch repeatedly over short distances. This suggests that as the lava moved forward, it congealed quickly and succeeding lava was obliged to take a new course. Marginal lava curls were developed near the source vents.

Finally, it should be noted that fragments of white rhyolitic pumice were expelled with the basaltic ejecta. The pumice is most abundant as fine ash, but large samples occur on the cone, chiefly about the north vent. Occasionally pumice is found encased within the black rind of a spindle-shaped basaltic bomb.

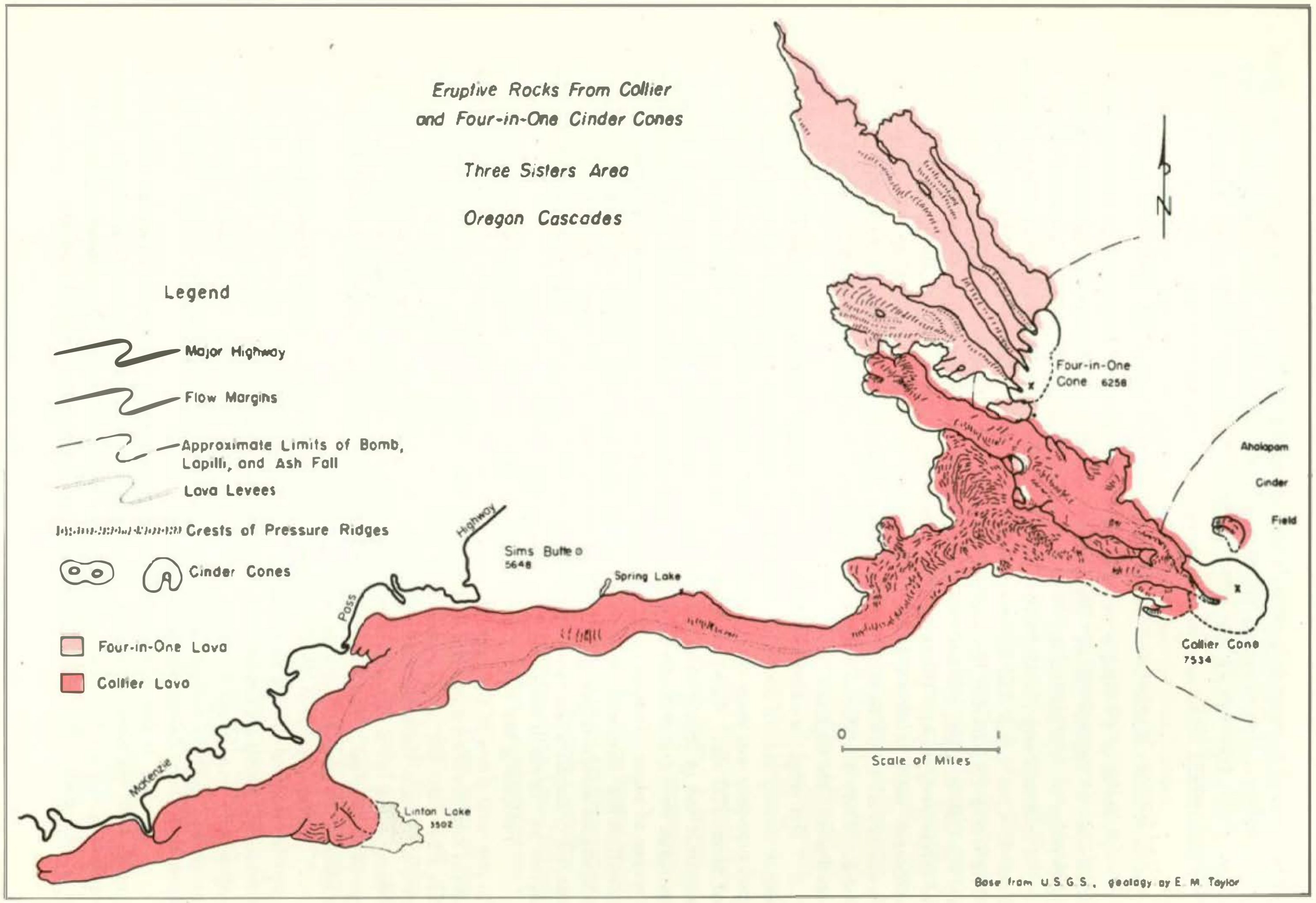

Eruptive Rocks From Collier
and Four-in-One Cinder Cones
Three Sisters Area
Oregon Cascades
Legend
Major Highway
Flow Margins
Approximate Limits of Bomb, Lapilli, and Ash Fall
Lava Levees
Crests of Pressure Ridges
Cinder Cones
Four-in-One Lava
Collier Lava
N
Four-in-One Cone 6258
Ahalapam Cinder Field
Collier Cone 7534
Sims Butte 5648
Spring Lake
Highway
Pass
McKenzie
Linton Lake 3502
0
1
Scale of Miles
Base from U.S.G.S., geology by E. M. Taylor

FIGURE 5.

Volcanic History of Collier Cone

Collier Cone lies at the north-by-northwest base of the North Sister and probably is, of the features described, the most recently active volcano. Stratified cinders and bombs are exposed in the crater walls. Black, fragmented bombs as much as one foot in diameter are abundant on the cone and may be found as distant as half a mile west and a quarter of a mile east of the vent. Fine-grained ejecta were driven eastward by the wind to form a square mile of alpine desolation, known as the Ahalapam Cinder Field. Vitrophyric pumice, often mixed intimately with basaltic glass, is common in deposits of Collier ash and scoria.

Collier flow rocks afford an unusually clear record of eruptive history. An estimated 0.04 cubic mile of lava issued from the cone, producing a west lobe $8\frac{1}{2}$ miles long and a northwest lobe 3 miles long (fig. 5). The lavas advanced in several distinct surges, each different in composition from its predecessor. Outward appearances of these flows, however, are remarkably uniform.

The initial lobe moved westward down the valley of White Branch Creek, blocking the drainage of a large spring to form Spring Lake at the base of Sims Butte. It then plunged into the Lost Creek glacial trough, damming Linton Creek to form Linton Lake. Relief of this west lobe, from source to terminus, is 4,160 feet.

The midsection of the lava stream, especially where it is steeply inclined, is occupied by long, multiple lava gutters. Several surges of lava must have poured down gutters formed previously, because two pairs of lava levees are nearly constant features of the early lobes and three pairs are fairly common.

A final surge of lava filled and overtopped the crater of Collier Cone, mantling its western slopes in a shroud of thin lava tongues. The northwest part of the cone was breached at this time and a large sector was rafted a quarter of a mile by the rising flood. As the breach widened the lava drained away, leaving a smooth coating on portions of the crater walls. The new lavas poured westward, narrowly confined between high levees. This last addition to the west lobe has been traced as far as Linton Lake but its furthest extent has not been recognized.

Several short, broad, subsidiary lobes were formed as lava spilled out of the gutters along the upper third of the west lobe - probably because the narrow channel could not accommodate the large volume of lava discharged into it. Perhaps for this reason, lava burst through an opening north of the breached area to form the northwest lobe. As activity shifted to the northwest, the supply of fresh lava to the west lobe diminished, and the blocky crust was folded into transverse, arcuate pressure ridges which now occur upstream from constrictions in its course. Final motion of the west lobe consisted of draining from the steeply inclined flow near the source vent. The deep gutter thus formed is now the most accessible route to the crater floor, and is occupied by the Skyline Trail. Before the northwest lobe chilled to its present form, a minor extension moved approximately 200 feet into the upper reaches of this gutter.

A few small lava tongues emerged at the north base of Collier Cone from a vent now buried beneath scoria and ashes. The position of these flow rocks in the eruptive history of the cone is uncertain.

At intervals throughout its length, the west lobe has been dissected by White Branch Creek. In the walls of these stream channels, the lobe is seen to be a mass of tumbled blocks and scoria. Close to the source, however, the blocky crust is underlain by dense glassy lava cut by deep transverse fractures.

During the past century, Collier Cone blocked the "Little Ice Age" advance of Collier Glacier. An early photograph (Campbell, 1924) shows Collier ice high on the flanks of the cone. When the ice attained a thickness of 200 feet at its terminus, meltwater was discharged into the crater, much of the floor was covered with outwash, and stream gravels were deposited for more than one mile down the west gutter. As the stream deposits near the cone are discontinuous and without interconnecting channels, the meltwater must have traversed snowfields and probably was active for only a brief time.

Continuity in the Volcanic Record

In the preceding descriptions, reference was made to more than 125 separate vents which have emitted various combinations of lava, ejecta, and gas. A number of genetic interpretations of the resulting landforms and deposits were offered. The shape of cinder cones, for example, depends upon such diverse factors as vent configuration, underlying topography, erosion, lava-breaching, explosive violence, and prevailing wind direction. The thickness of flow rocks and their surface features, aerial distribution, and sequence of superposition are determined by available topographic channels, viscosity and volume of lava, eruptive chronology, and the nature of the volcanic "plumbing" in the subsurface. The interdependence which exists between some of these factors is critical to petrologic interpretations.

Persistent linear vent patterns suggest that systems of faults or fractures must underlie the volcanoes. The most obvious alignments are those of the Sand Mountain groups, Inaccessible Cone, Four-in-One cones, and the Yapoah-Collier vents. While caution must be exercised in tracing vent alignments over long distances, the trend displayed by the Belknap craters, the Spatter Cone Chain, and Blue Lake Crater probably represents a similar continuous connection at depth. Close study of the eruptive centers, however, reveals several interesting irregularities. Some alignments (Four-in-One, for example) are linear over short segments but arcuate over their full length. Nearly all vent patterns except Belknap - Spatter Cone - Blue Lake and Four-in-One, trend individually north-south even where the composite alignment is differently oriented (Nash Crater, for example).

With few exceptions, each cinder cone is associated with a swarm of subparallel, north-south vegetation lineaments which are seen best on stereographic pairs of aerial photographs. These lineaments are composed of trees which stand 10 to 30 feet above the surrounding forest. Several lineaments are visible from mountain tops, but only one, on the west flank of Bachelor Butte, has been traced directly on the ground. They are not observed, of course, above timberline or in deforested areas. As seen on a photo scale of 1:50,000, some of the lineaments are only 30 to 50 feet wide, are as much as five miles long, and are nearly straight when plotted on a planimetric base.

The origin of such lineaments is not well known. None transect the most recent of the forested flows, but older lava fields display them in profusion. They occur with greatest frequency upon High Cascade glaciated bedrock which is overlain by thin deposits of ash or ground moraine. While the lineaments are not restricted to areas of Recent volcanic outbreak, they are concentrated near cones and usually a vent pattern coincides perfectly with a lineament. The following interpretation is offered on a provisional basis: Linear patterns of accelerated forest growth reflect irregularities in the supply of ground water which are, in turn, influenced by a bedrock joint set. Because the forest cover generally is scanty on glaciated bedrock surfaces, it is difficult to correlate lineaments on the map with joints in the rocks. If such a joint set exists, it is parallel to the length of the High Cascades and, for the most part, predates Recent volcanism. Volcanic conduits, rising above a broad, magmatic alignment were influenced by the joints. Consequently, the vent patterns generally trend north-south even if the alignment of which they are a part does not. Lineaments of the lava fields are commonly arcuate and concave toward the source cones, and may represent fracture systems above a subsiding magma column.

If the above interpretation is correct, it is likely that vents of a single eruptive center, coincident with a vegetation lineament, were active at about the same time. To what extent can this principle be applied to a whole alignment of eruptive craters? The answer is contained in the statement of lava chronology given in Table I below.

The central column in Table I is an eruptive sequence based upon radiocarbon age determinations, glacial records, and direct superposition of lava flows and ash deposits. Whether or not the approximate correlations in the third column are accepted, it will be seen that strict, detailed interpretation of an alignment as

TABLE I. Lava Chronology

Dates	Eruptive Sequence		Approximate Correlations
Older than 400 years	Collier		
	Four-in-One		
	Yapoah		
	Little Belknap		
	South Belknap flows		
360 A.D. ± 160 (WSU-292)	West Belknap flows		
1000 B.C. ± 220	Clear Lake flow	..?..	S. vent Sand Mtn.; Twin Craters; Sims; Condon; Little Nash
1500 B.C. ± 250 (WSU-291)	Blue Lake Crater	..?..	Latest flow, South Group; Fish Lake, Lava Lake flows; Spatter Cone Chain.
	Central Group and earliest flows from Nash, Sand, South Group; most of the ash from Sand Mtn. Alignment	..?..	Lost Lake Group
	Cone and flow of N. Inaccessible; two old cones of N. Sand Mtn. Alignment; Hoodoo	..?..	S. cones and flows of Inaccessible Alignment
Older than 10,000 years?	Flows and cones of quest. Recent age.		

consisting of coeval rocks is hazardous. The over-all eruptive sequence, however, is clearly related to geographic position; the eruptive history progressed from northwest to southeast. Exceptions to this rule are few and represent a comparatively modest volume of lava.

Several physical characteristics of lava flows in the area of study can be correlated with this eruptive sequence. For example, early lavas were relatively fluid and for this reason formed voluminous shields and extensive lava fields of thin flows with complex, discontinuous drainage patterns. Later lavas were more viscous, and were erupted in lesser volume; they formed thick flow units with high-standing margins and developed pressure ridge and lava gutter systems which are continuous for miles. In Part II of this paper, to be published at a later date, the results of petrographic studies and more than 200 partial chemical analyses will be placed within this framework of volcanic stratigraphy, and it will be shown that textural, mineralogical, and chemical characteristics of the lavas change in a regular way through the eruptive sequence.

Many details of the Recent volcanic history of this interesting region remain unknown. In particular, correlations must be extended over a larger area and additional radiometric dates must be obtained. The evidence at hand suggests that an elongate zone of volcanic activity cuts obliquely across north-south lineaments of the High Cascades in the vicinity of the Three Sisters. It may be continuous with a similar volcanic trend between the Three Sisters and Newberry Caldera to the southeast. For more than 10,000 years intermittent eruptions of basalt have occurred over the northwest extension of this zone, and during the last 4,000 years volcanic activity has shifted from northwest to southeast. The duration, recency, and continuity of such a record all suggest that future eruptions are possible in spite of the brief period of quiescence during historic time.

Acknowledgment

Radiocarbon dates were financed through a Northwest Scientific Association Grant-in-Aid. The writer is indebted to Dr. R. M. Chatters of the Washington State University Radiocarbon Laboratory for his help and advice, and to Roald Fryxell for many fruitful discussions concerning Recent geochronology of Oregon and Washington.

Glossary of Selected Terms

Accidental fragments. Rock particles erupted from a volcanic vent which are foreign to the magma associated with the vent.

Agglomerate. An accumulation of volcanic ejecta, usually near a vent, in which most of the particles are larger than scoria.

Agglutinate. A deposit of mixed bombs and spatter, more or less consolidated.

Ashes. Unconsolidated particles of volcanic ejecta, smaller than scoria.

Blocks. Angular fragments of volcanic ejecta, larger than scoria. Also applied to crustal fragments of lava flows.

Bocca. An Italian term meaning vent. English usage generally refers to a lava vent at the base of a cinder cone.

Bombs. Volcanic ejecta of any size which have assumed a rounded, aerodynamic shape during flight and have retained a recognizable vestige of this shape after impact.

Composite volcano. A volcanic mountain, generally large, in which lava is as abundant as ejecta. Opposed to cinder cone, generally small, in which ejecta predominate.

Lapilli. A class of volcanic ejecta which includes scoria and accidental fragments of scoria size.

Lapilli-tuff. A deposit of consolidated lapilli and ash.

Lava fields, flows, lobes, and tongues. A lava field is a wide and complex expanse of lava flows from separate, but related, vents. A flow is made up of lava from a single vent or from a small source area of closely related vents. Lobes are separate and distinct lava streams belonging to a single flow. A lava tongue is, as the name implies, a small, tongue-like offshoot from a flow.

Lava gutters and lava levees. If the supply of lava to an established channel rapidly diminishes, and if the flow gradient and fluidity is sufficiently great, the medial portion may drain away leaving a long deep gutter. Lava gutters are often bordered by high-standing margins called lava levees.

Pressure ridge. Broad ridges of lava, transverse to the direction of flow. Generally arcuate in plan, concave upstream, and thought to result from differential movement between a stagnant crust and a mobile interior.

Recent. A feature is considered to be of Recent geologic age if it came into existence since the last major glacial episode (here estimated to be 10,000 - 12,000 years ago).

Scoria. Particles of volcanic ejecta having coarse vesicular habit, irregular form, generally basaltic composition, and variable BB-shot (4mm) to walnut (32mm) dimensions.

Shield volcano. A large, broad volcanic mountain with gentle slopes of constructional rather than destructional origin.

Spatter. Irregular clots of ejecta, larger than scoria, but not highly vesicular; similar to bombs in origin but not in shape.

Squeeze-ups. Protrusions of lava extruded through rifts in a solid crust.

Steptoe. An elevated point of land surrounded by lava flows.

Vesicles. Rounded gas-bubble cavities in lava rocks.

Vitrophyric. The texture displayed by predominantly glassy lava which contains abundant megascopic crystals.

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NOTABLES TO ATTEND INTERNATIONAL LUNAR CONFERENCE

Nearly 100 scientists from 12 foreign countries and the United States will participate in the International Lunar Geological Field Conference in Bend, Oregon, August 22-28. The scientists are authorities in astronomy, geology, astrophysics, and related fields. Included in the roster of those attending are such names as Dr. Shotaro Miyamoto, Kyoto University, Japan; Dr. Harouin Tazieff, University of Brussels, Belgium; Dr. Aleksandr Mikhailov, Main Astronomical Observatory, Soviet Union; Dr. Nikolay Kozyrev, Physico-Mathematical Sciences, Leningrad; and Dr. Gerard Kuiper, Lunar and Planetary Observatory, University of Arizona.

The Conference is being co-sponsored by the New York Academy of Sciences and the University of Oregon, and is intended to advance investigation into the nature of the lunar surface. At least 10 papers will be presented and discussed by the participants, and five days will be spent on field trips in the area around Bend.

Dr. Jack Green, New York Academy of Sciences, and Dr. Lloyd Staples, Department of Geology, University of Oregon, are co-chairmen of the conference. Other members of the general committee are Lawrence A. Dinneen, Oregon Division of Planning and Development, Hollis M. Dole, State Geologist; and Marion Cady, Lunar Base Research Facilities, Inc., Bend.

KGW-TV, Portland, plans a program on the Conference August 22 at 11:30a.m.

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CENTER FOR VOLCANOLOGY

Dr. A. S. Flemming, President of the University of Oregon, has announced the establishment of a Center for Volcanology in the Department of Geology. Named as Director of the Center is Dr. A. R. McBirney, who will come to the University of Oregon from the University of California, San Diego, at LaJolla. He has done extensive work in volcanic regions in Central America, and is the author of many papers on volcanic activity.

The decision to establish a Center for Volcanology at the University of Oregon was based on the fact that the State of Oregon contains areas of volcanism, ancient and recent, unsurpassed in variety and scientific interest. More than half of the State is underlain or covered by volcanic rock, much of it extruded during Tertiary and Quaternary times. The Recent cones, flows, and pyroclastic deposits have changed very little since they were formed and are excellent laboratories for field studies.

The early planning of the Center was done by a committee consisting of Dr. A.C.Waters, University of California, Santa Barbara; Dr. Howel Williams, University of California, Berkeley; Dr. Gordon Macdonald, University of Hawaii; Mr. P. D. Snavely, U.S. Geological Survey, and Dr. L. W. Staples, University of Oregon. Dr. Staples, who is Head of the University of Oregon Department of Geology, announced that one of the first activities of the Center for Volcanology will be the co-sponsoring with the New York Academy of Sciences of an International Lunar Geological Field Conference in Bend August 22 to 28. About 17 lunar geologists from abroad and 32 from the United States have indicated their intention of attending the conference. Many scientists will read papers and all will participate in five days of field trips to volcanic features similar in appearance to lunar topography shown by the pictures taken by Rangers 7, 8, and 9.

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CRACK-IN-THE-GROUND, LAKE COUNTY, OREGON

By

Norman V. Peterson and Edward A. Groh

CRACK-IN-THE-GROUND, LAKE COUNTY, OREGON

By

Norman V. Peterson* and Edward A. Groh**

Open cracks or fissures in the earth's surface are not uncommon; they occur fairly often as a result of earthquakes or volcanic activity, but they usually become filled with rock rubble or lava and disappear in a very short time. A large fissure that stays open for hundreds of years is, therefore, a rare feature. Such a fissure occurs in a remote part of central Oregon. It is a deep, narrow rift about 2 miles long, and it has remained open for perhaps a thousand years. For lack of any official name for it, the feature is referred to simply as "Crack-in-the-Ground."

Location and History

Crack-in-the-Ground is situated in northern Lake County in T.26 S., R. 17 E. As shown on the accompanying geologic sketch map (plate 1), it can be traced from the southwest edge of the Four Craters lava field diagonally to the southeast until it disappears in lake sediments that mark the north shoreline of prehistoric Christmas Lake.

The feature can be reached by road, but the last few miles are not suitable for cars with low road clearance. The route starts from the east side of Silver Lake on Oregon Highway 31. From this point the course leads 19 miles northeast on a paved road to Christmas Valley Lodge, then east on a graveled road 1 mile and north on a graded dirt road 4 miles. At this mileage a rough, bouldery road branches off to the left and winds northwesterly through the sagebrush. It approximately parallels the west side of the fissure for 2 miles and then skirts the western edge of Four Craters lava field (see map). This road passes within 150 yards of the northern end of Crack-in-the-Ground, where lava has flowed into the fissure and filled it.

Homesteaders in the area have known about this giant fissure for many years. Reuben Long of Fort Rock, Oregon, reports (written communication,

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1964) that when he lived at Christmas Lake as a boy he used to explore "The Crack," as it was called locally. He remembers that the homesteaders went there to hold picnics and make ice cream, using ice they found in caves in the chasm.

Description

Crack-in-the-Ground is a tension fracture in basalt. The walls are rough and irregular and show no lateral and but very slight vertical movement. The crack is open for a distance of more than 2 miles, but continues to the northwest and southeast as a trace which, although not visible on the ground, is revealed on aerial photographs. Where best developed, the fissure is from 10 to 15 feet wide at the top, narrowing downward. The depth varies, but is as much as 70 feet in some places. Figures 1 and 2 are aerial views of the crack and figures 3 and 4 are closeups.

Erosion and weathering have been at a minimum in this desert climate of northern Lake County, but over the many years that Crack-in-the-Ground has existed, some rock has sloughed off the walls and sand has blown or washed in to fill the bottom. At several places the walls have slumped, thus bridging the gap and allowing access to the deeper parts of the fissure. Winter ice is sometimes preserved during the summer in the deeper, more cavernous places where cold air is trapped.

Geologic Setting

Crack-in-the-Ground is closely related to the Four Craters lava field, one of the many isolated centers of recent volcanic activity within the high lava plains of central Oregon. Older rocks in the map area which pre-date the breach but which are broken by it include several ages of volcanic rocks and lake-bed sediments as described below.

Lake beds and alluvium

Large, shallow lakes filled the broad Fort Rock-Christmas Lake Valley beginning in late Pliocene time and continuing intermittently through the Pleistocene. During the Recent epoch, these lakes gradually shrank to small, brackish potholes and irregularly shaped saline pools. Lake beds, alluvium, and wind-blown materials of varying thicknesses mantle the floor of the basin, and wave-cut terraces around the rims represent various levels of the ancient lakes.

Explosion tuffs

The oldest volcanic rocks exposed in the area are erosional remnants of maars or tuff rings of late Pliocene to Pleistocene age. The remains of a maar just west of the Four Craters lava field is shown on plate 1. This mass of yellow-brown basaltic tuff and breccia is similar in composition and layering to Fort Rock and other remnants of maars and tuff rings, which were once numerous and widely distributed in and around the edges of the large lake basins of central Oregon (Peterson and Groh, 1963-b).

Green Mountain basalt

Surrounding the basaltic tuff remnants are younger basaltic lava flows that originated from Green Mountain, an eruptive center immediately to the northwest of the map area. The Green Mountain lavas form a low shield some 10 to 12 miles in diameter. The flows on the southern edge encroached on the pluvial lake that then filled the Fort Rock-Christmas Lake Valley and became the northern shore line. These lavas are of the pahoehoe type. Where they are exposed in the walls of Crack-in-the-Ground there are two or more flows with an overall thickness of at least 70 feet. Their surface is masked with a thin layer of soil composed mainly of fine pumice, windblown sand, and silt from lake beds in the adjacent Fort Rock-Christmas Lake Valley. Tumuli and other flow-surface features are present. Several small cinder cones near the summit of the Green Mountain shield still retain most of their initial characteristics even though they are covered by vegetation. From these observations, the Green Mountain lava is believed to be of late Pleistocene age.

Four Craters basalt

The Four Craters lava field, named in an earlier report (Peterson and Groh, 1963-a), formed from basaltic lava that flowed mainly south and east from centers along a fissure trending N. 30° W. The sluggish flows piled up a hummocky layer of black, spiny aa lava on the slightly sloping Green Mountain lava surface. Four cinder cones aligned along the fissure rise from 250 to 400 feet above the lava surface. The distance from the northernmost cone to the southernmost is roughly 2¼ miles. The southernmost cone is especially interesting, because several sectors of it were rafted off to the southeast on a slightly later lava flow. The freshness of the lava and lack of soil and vegetation on the surface indicate a Recent age for this field.

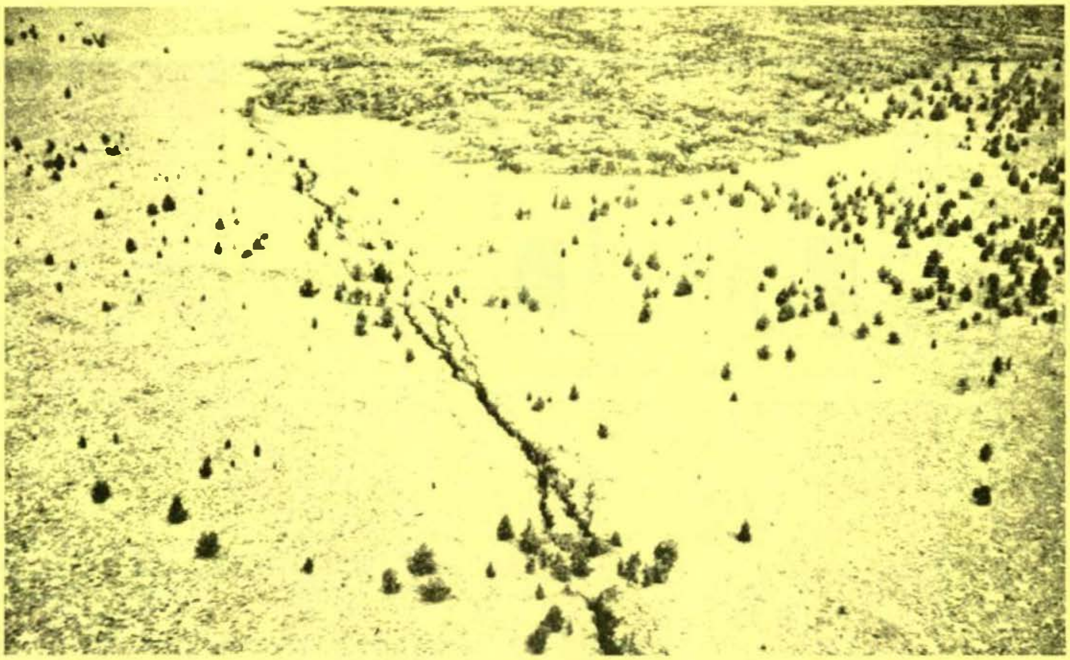


Figure 1. Aerial view of Crack-in-the-Ground looking north-northwest. Four Craters lava field in the background. Road shows in upper left corner.

Figure 2. Looking down on a portion of Crack-in-the-Ground. The fissure has been filled and bridged over in the center of the picture.

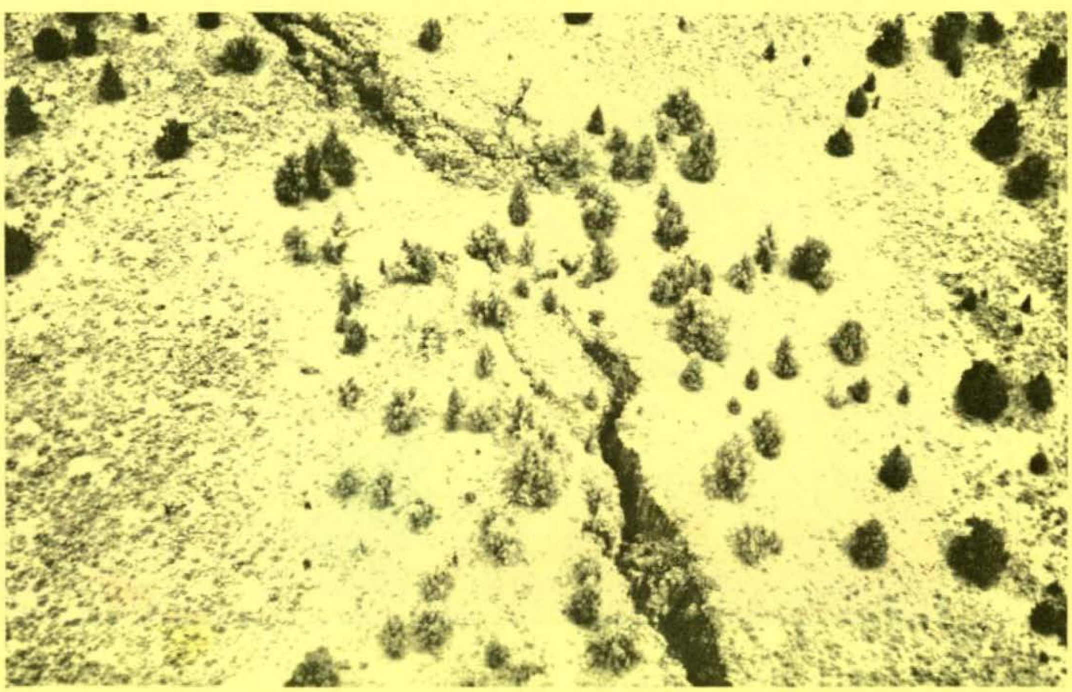
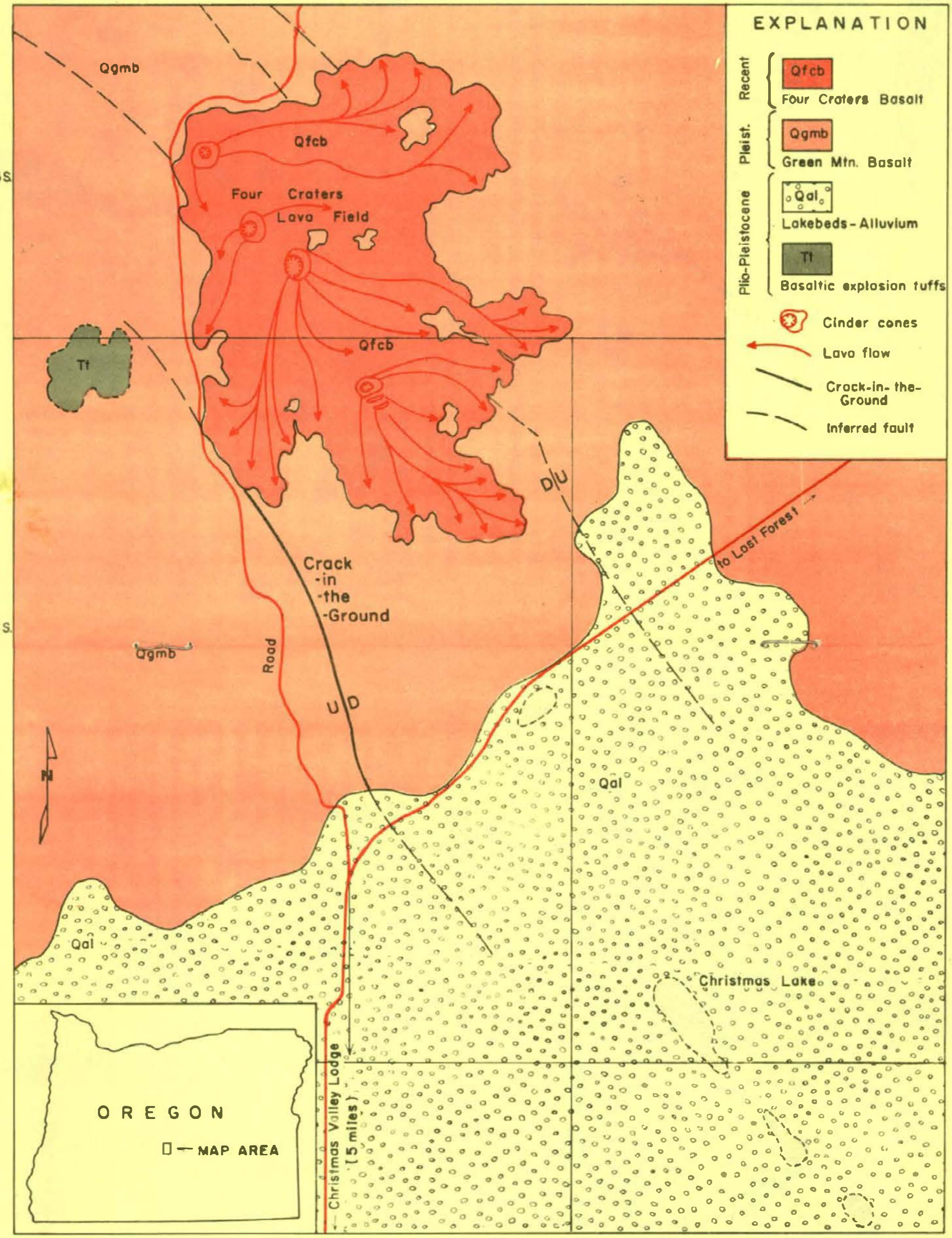


Plate 1. Geologic Sketch Map of the Crack-in-the-Ground Area.



Map adapted from aerial photographs.

Map prepared by
STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES

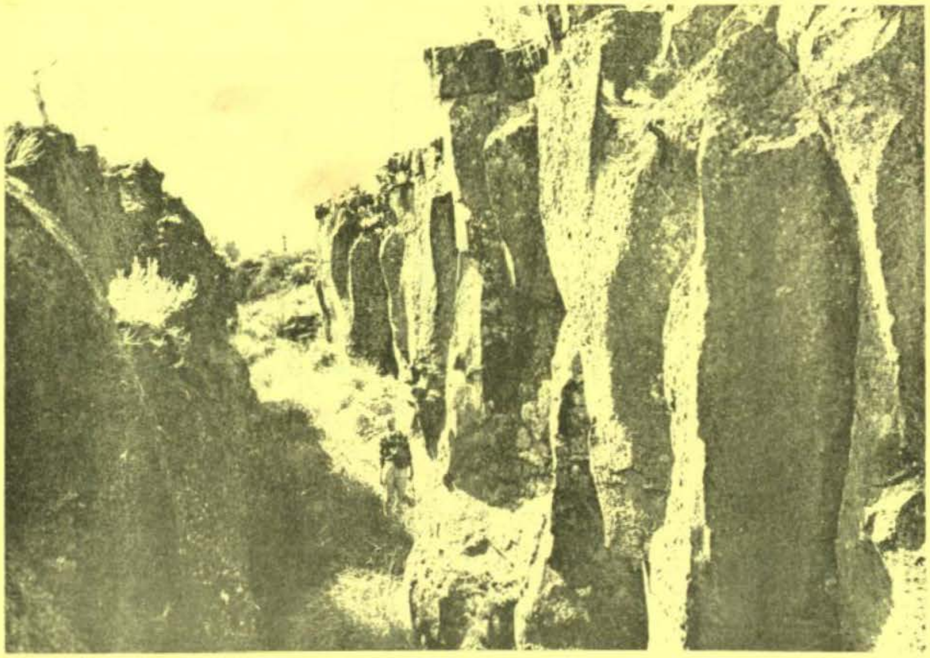


Figure 3. View of Crack-in-the-Ground showing the irregularity of the walls and fill in the bottom.

Figure 4. One of the deeper portions of Crack-in-the-Ground where access can be had from the surface. (Black lines drawn to define walls.)

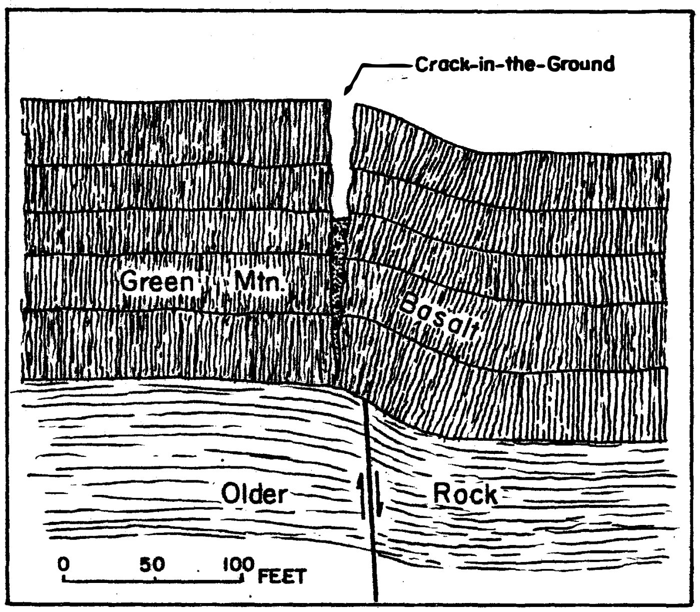


Figure 5. Generalized geologic cross section of Crack-in-the-Ground.

Origin of Crack-in-the-Ground

The eruptions from the Four Craters were accompanied by a slight sinking of the older rock surface to the southeast. This shallow, graben-like sink is about 2 miles wide and extends to the south into the old lake basin. Crack-in-the-Ground marks the western edge of this small, volcano-tectonic depression and parallels a zone of weakness concealed beneath the Pleistocene Green Mountain lava flows. The fracture is the result of rupture from simple tension along a hingeline produced by the draping of the Green Mountain flows over the edge of the upthrown side of the concealed fault zone (figure 5). The initial fracturing was probably propagated rather quickly over its length as the central block began to sink to form the shallow graben. Vertical displacement of the graben is no more than 30 feet and it diminishes to the southeast. There is the suggestion that the shallow graben continues on into the old lake basin and acts as a sump for present-day Christmas Lake and other ephemeral ponds and potholes. The sinking of the graben block and the accompanying rift on its western edge probably began with the first eruptions of the Four Craters. Crack-in-the-Ground opened before the last volcanic activity, and at its northwest end a tongue of lava piled up, tumbled into, filled, and buried the chasm for several hundred yards.

Conclusion

The eruption of the Four Craters Lava, the accompanying subsidence, and the opening of the Crack-in-the-Ground fracture probably took place no more than 1,000 years ago. Even though some filling by soil wash and windblown material has taken place, and some slumping of blocks from the walls has occurred, the crack is a relatively fresh geologic feature. This stark freshness is partly the result of subdued chemical weathering in the arid climate and a lack of any recent violent earth movements or renewed volcanic activity in the immediate area.

A system of tension fissures similar to Crack-in-the-Ground has been previously reported in the Diamond Craters by Peterson and Groh (1964), but none of these has as great a length or depth. Another fault-fissure zone that trends northwest from Newberry Volcano to Lava Butte south of Bend, Oregon, has been studied by Nichols and Stearns (1938). This fissure is associated with the recent volcanism of the area and stands open in several places.

Further investigations in the field, together with study of aerial photographs, may reveal the existence of other interesting cracks in remote parts of Oregon where volcanism and faulting have occurred.

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DIAMOND CRATERS, OREGON

By Norman V. Peterson* and Edward A. Groh**

Introduction

Diamond Craters is the name given to an isolated area of recent volcanism near the center of Harney County in southeastern Oregon. The area lies about 60 miles south of Burns in Tps. 28 and 29 S., R. 32 E.

The whole of this volcanic feature is not easily described, but it probably fits most correctly the definition of a small shield volcano. The first volcanic activity produced a field of lava that was shaped much like a huge pancake about 6 miles across (see plate 1). This lava welled up and flowed out in radial directions from a now-hidden vent near the center. Slight irregularities in the topography over which the coalescing tongues of lava flowed created a design at the perimeter resembling the scalloped edges of a lace tablecloth. Later on, sporadic volcanism, both explosive and quiet, domed, split, and pockmarked the original relatively smooth surface producing a concentrated variety of stark, fresh volcanic landforms.

Diamond Craters were known to the early settlers of eastern Oregon and were named about 1875 for their proximity to the Diamond Ranch. This ranch took its name from the diamond-shaped cattle brand used by Mace McCoy, an early settler. The name Diamond was also given to a small community and post office nearby. Even though the craters are remote from population centers, access is not difficult. The easiest route is southeast from Burns on Oregon State Highway 78 to the junction at New Princeton, then south and west by well-marked, all-weather roads that skirt the east and south parts of the Diamond Craters. A well maintained dirt road crosses the broad, cratered and domed area from east to west on its southern flank. This road passes between or near many of the most interesting landforms, as shown on the index map in plate 1.

The names given to the numbered features on the index map and referred to in the text are only for the purpose of the report.

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Previous investigations

I. C. Russell (1903), one of the first geologists to make a reconnaissance of eastern Oregon, visited Diamond Craters in 1902. He gives a rather comprehensive description of many of the craters and other features. From his observations he described lapilli cones and lava cones as the principal features of the area. He mistakenly interpreted the low dome on the northeast side, feature No. 5, to be a cone built up of layers of lava flows. If he had been able to view this feature from above or to see aerial photographs of it, he would most certainly have realized that this is a structural dome, bowed up by the pressure of intruding magma. Russell gives an interesting description of the large crater complex (feature No. 1) at the center of the Diamond Craters field and also details of the small graben (feature No. 7) which he calls a gulf. He also mentions the peculiar spherical lava balls or bombs found in the low rims of most of the craters of explosive origin but does not postulate as to their origin.

Rocks of the Diamond Craters have been mapped as "late basalt and ejectamenta" of latest Pleistocene to Recent age (Piper and others, 1939). The lack of any appreciable erosion was believed to indicate that some of the volcanic activity may have taken place only a few hundred to a few thousand years ago. Piper and others (1939) refer to the Diamond Craters as "a basaltic lava field whose predominant feature is a lava dome whose crest is broken by a linear pit."

Field work

This study of Diamond Craters is part of a project of the State of Oregon Department of Geology and Mineral Industries to evaluate the recent volcanic landforms of Oregon. The field work was done on the ground on August 6, 7, and 8, 1963. On August 21 the area was viewed and photographed from various elevations in a small airplane. Available aerial photographs from government sources were also used to help determine the sequence of volcanic activity.

Geologic Setting

The Diamond Craters area is at the very southern edge of the broad alluvial plain of the Harney Basin. Just to the south are the dissected uplands of the long westward slope at the northern end of Steens Mountain. From this dissected upland the Donner und Blitzen River, Kiger Creek, and McCoy Creek enter the Harney Basin to meander to Malheur and Harney Lakes, shallow playa lakes that form the sumps for the large undrained basin. Riddle Creek, a little farther to the east, once joined the Donner und Blitzen just west of the Diamond Craters, but its course was dammed by the first flows of the Diamond Craters lava and it now turns northward and empties into shallow Barton Lake. Kiger Creek was also forced to the south and west by the encroaching Diamond Craters lava.

The rocks immediately beneath and surrounding the Diamond Craters are geologically young. Piper and others (1939) have separated them into three mappable units. The oldest rocks are the Danforth Formation of Pliocene age, made up of stratified siltstones, sandstones, and tuffs with at least one prominent layer of welded tuff. This is the most widespread rock unit directly beneath and surrounding the Diamond Craters on the south and west. A younger Pliocene formation, the Harney Formation, contains massive basaltic tuffs and breccia layers, sandstone, and siltstone, with a prominent capping layer of basalt. The Harney Formation is present to the north and east of the Diamond Craters as isolated mesas and other erosional remnants perched on the Danforth Formation. The youngest of the three units is a lava field that Piper and others (1939) have called the "Voltage Lavas." This lava flowed out on an erosional surface and surrounded the isolated remnants of the Harney Formation. Its surface shows some weathering and a thin layer of soil is present. From this evidence it is estimated (Piper and others, 1939) that the lava was probably erupted during Pleistocene time, much earlier than the Diamond Craters lava.

Volcanic History of the Diamond Craters

The original land surface, before the first eruptions of the Diamond Craters lava, was very nearly as it is now. Erosion had removed all but a few patches of the Harney Formation from the basin. Alluviation of the central part had already begun, because drainage to the Malheur River and ultimately to the Snake River to the east had effectively been dammed by the flows of Voltage Lavas. The streams draining the western slopes of Steens Mountain were bringing in more sediment as they meandered across the flat valley floor to Malheur Lake.

The first event in the formation of the Diamond Craters was the eruption of a very fluid olivine basalt from a single, or a few closely spaced, vents along a zone of weakness that trends northwest through the area. The eruptions were probably preceded by earth tremors as a fissure opened at depth and the magma began its upward rise from a small independent reservoir. The lava flowed out from a source the type and location of which cannot now be determined because of obliteration by later volcanic activity. It probably existed in the vicinity of what is now the Central Crater Complex, indicated by the radial pattern of the lava flows. The lava spread out

Figure 1. Aerial view ot the pahoehoe lava surface in the northeast part of the Diamond Craters lava field. As the flood of fluid lava spread farther from its source, a thin, rubbery, undulating crust was formed. The waning supply of lava drained beneath the cooling crust through a system of lava tubes and channelways. The lava roofs, already weakened by shrinkage joints and cracks, collapsed into the voids to form sinks of many sizes and shapes. In this view some of the depressions resemble giant foot tracks 100 to 200 feet long; others are small and nearly circular. These collapse depressions are characteristic of pahoehoe lava fields.

Figure 2. Oval Crater. The west end of a long, oval crater which formed as the vent shifted from east to west over an extended period of sporadic explosivity. The low, rounded rims are made up of lapilli and bombs. The truncated edges of pahoehoe lava flows can be seen in the crater walls. At this west end it is 900 feet from rim to rim; the long oval crater extends for 2,000 feet to the east.

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rapidly as pahoehoe flows to cover roughly a 6-mile-diameter circular area. In the final stages much of the pahoehoe crust foundered into drained lava tubes producing abundant, well developed collapse depressions (figure 1). Thickness of these lava flows is estimated to be 75 to 100 feet in the center of the field, thinning to a foot or so at the margins.

Following this initial relatively quiet eruption of lava, the sequence and time duration of volcanic events becomes slightly more obscured, but from viewing the aerial photographs and examing the features in the field, it is judged that their general sequence is probably thus:

A. A renewed upward surge and lateral intrusion of basaltic magma into the sediments of the Danforth Formation bowed up parts of the newly formed circular lava field into three low, rounded domes, aligned generally northwest-southeast above the fissures through which the magma rose. The most westerly of these is just north of the Twin Craters on the index map. The second and highest elongate dome is now modified by the Central Crater Complex, and the third has been somewhat modified by Oval Crater.

B. Accompanying and closely following this doming, gas from the vesiculating magma plus steam, which was generated as the magma heated water-saturated rocks, furnished energy for explosions of varying violence to form craters of different sizes and types. Many of these craters were subsequently enlarged by engulfment or collapse after the explosive eruptive stage, leaving little or no rims of ejecta. Twin Craters, and Oval Crater (figure 2) are two examples. Others such as Malheur Maar (figure 3) and Cloverleaf Crater (figure 4) have rims of ejecta containing a considerable number of accidental fragments and show evidence of little or no collapse. Red Bomb Crater (figure 5) and Big Bomb Crater, on the other hand, have built shallow cones made up of lapilli, scoria, and a multitude of red and black spherical and ellipsoidal cored bombs (described in more detail on page 29). These craters are more like cinder or scoria cones,

Fig. 1

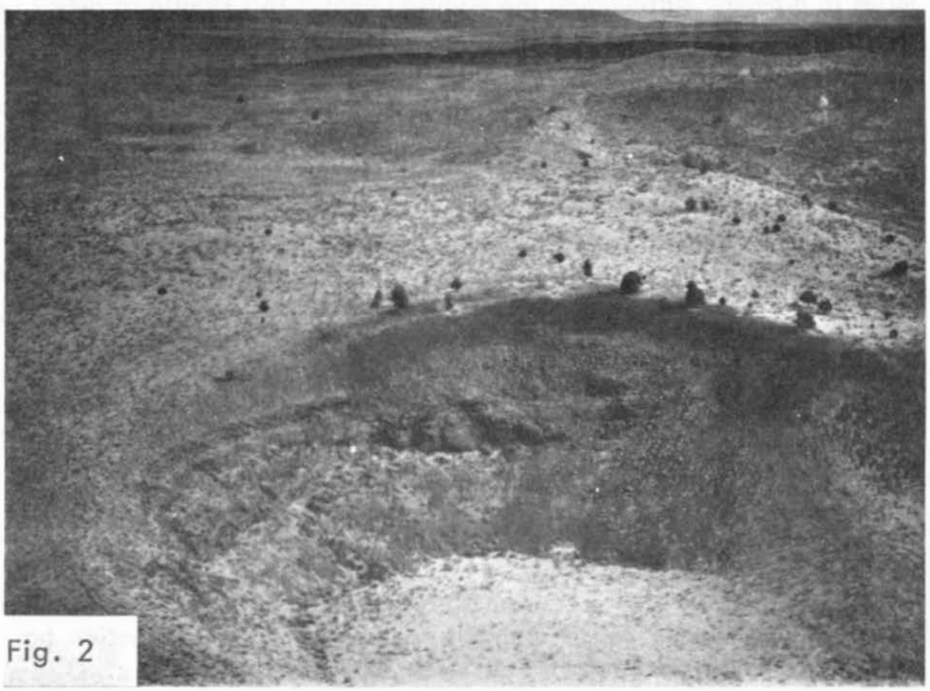

Fig. 2

Figure 3. Malheur Maar. This lake-filled explosion crater and an adjoining one fit the original definition of a maar. The feature is 250 feet in diameter and 100 feet deep. It was probably formed by one or more gas eruptions or steam blasts. Very little or no magmatic material was erupted and only low rims of broken rock fragments are present. On the pahoehoe surfaces in the background are low, rounded to oval bulges called "tumuli." These are believed to form when the partly congealed lava crust is raised by a local build-up of lava immediately beneath it. The tops of many of the tumuli are cracked open, and molten lava from below has squeezed up into some of the cracks.

Figure 4. Cloverleaf Crater. Brief sporadic explosions from separate, closely spaced vents formed this multiple-lobed crater rim that surrounds individual shallow craters. The several small craters occupy an area about 600 feet in diameter.

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since there is a larger addition of magmatic material in their composition.

C. At the close of the above eruptive phase, new activity was concentrated at the Central Crater Complex (figure 6). Additional doming by intrusion of the magma was followed by violent explosive eruptions that perforated the roof and showered broken rock and ash high into the air. To a contemporary observer, a mushrooming cloud of vapors and ash would have been seen billowing to a great height. Pulverized rock and comminuted ash fell back from this cloud to form a thin masking layer about 5 miles in diameter surrounding the erupting vent. This mantle of debris can be seen in the aerial photo (plate 1) as a halo encircling the Central Crater Complex. Eruptions continued less frequently and less violently from vents that shifted within the eruptive center until at least 17 funnel-shaped crater pits, of which not all are represented on the index map, were formed amid the hummocky debris. These inner crater rims, like the rims of the smaller explosive features to the south and east, contain basaltic lapilli, scoria, and similar cored bombs mixed with rock fragments of many sizes and varieties. Fragments and blocks of gray welded tuff characteristic of the Danforth Formation are common to abundant, and a large outcropping of this same tuff is present high in the wall of one of the smaller inner craters. This is strong evidence for the conclusion that considerable doming had taken place prior to the eruptions. After all the explosive activity had ceased, fluid basaltic lava again welled up and formed several small flows which filled in slight depressions at the outer edges of the crater complex.

This volcanic feature is certainly an unusual one, and a detailed study would probably show that many individual volcanic episodes are responsible for its present configuration. The explosive eruptions must have fractured the whole mass, causing subsidence or collapse, which action has also been a factor in producing the shape of this crater complex. The

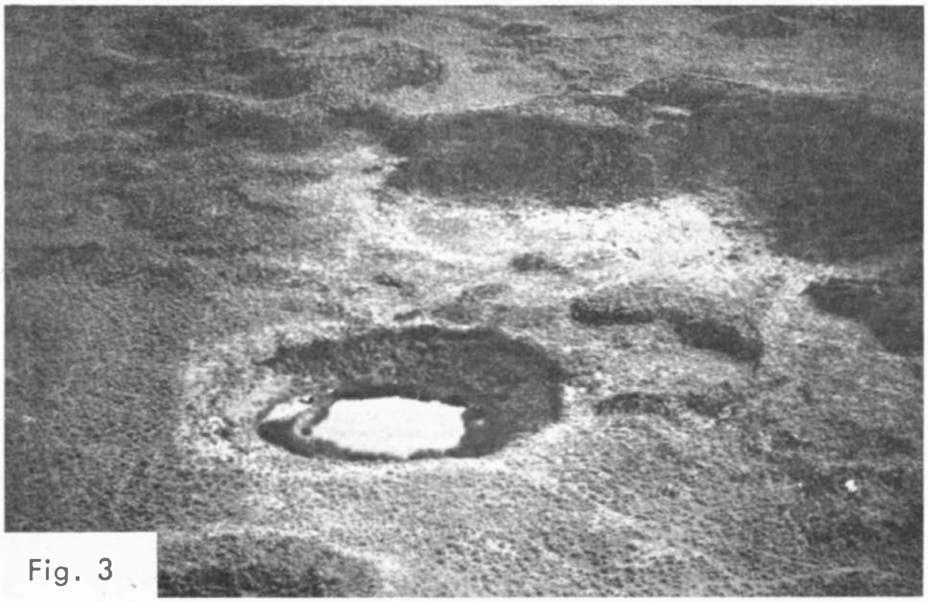

Fig. 3

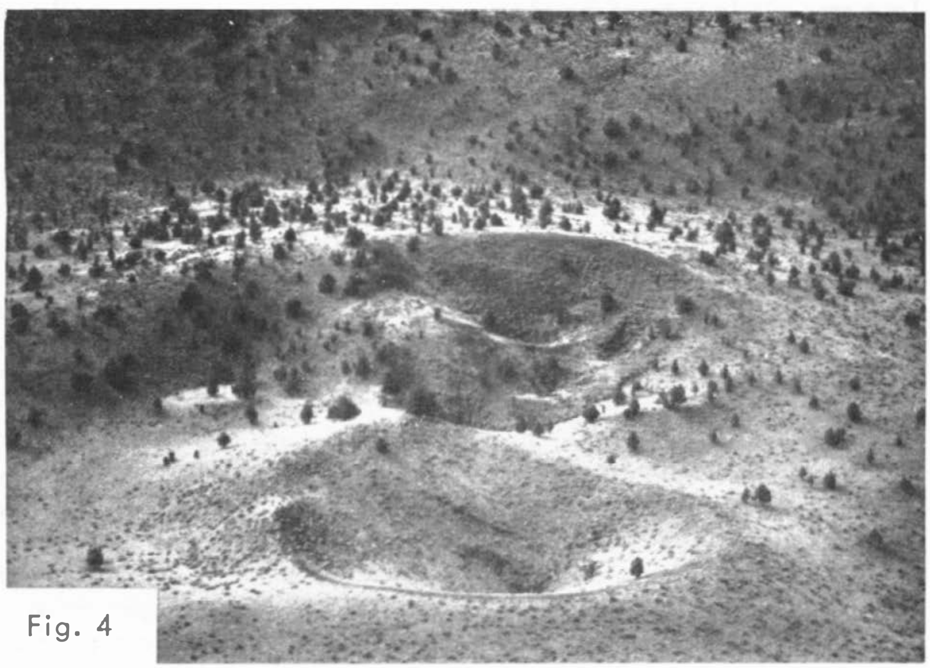

Fig. 4

Figure 5. Red Bomb Crater. A portion of Red Bomb Crater showing a scalloped rim and multiple funnel-shaped crater pits within a larger one that is more than 900 feet in diameter. The latest explosive eruption came from the crater in the lower left. The rims consist of accretionary lapilli and numerous bombs.

Figure 6. A small part of Central Crater Complex. Rather than being round or oval like most craters, it is rectangular with rounded corners. The feature is 1 mile long and 3,500 feet wide. The crater floor is as much as 200 feet below the rims near the outside edges, but the center is choked with piles of debris that are as high as the encircling rims. Within the hummocky debris there are at least 17 individual funnel-shaped craters with steep slopes and narrow bottoms. Part of this debris is accidental and part is magmatic in the form of cinders, scoria, and bombs. Fresh black lava in small amounts has stoped upward to fill depressions near the edges of the crater.

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funnel-shaped bottoms of the inner craters and the loose debris still lying at steep angles on the walls attest to a very recent origin, probably within the last 1,000 years.

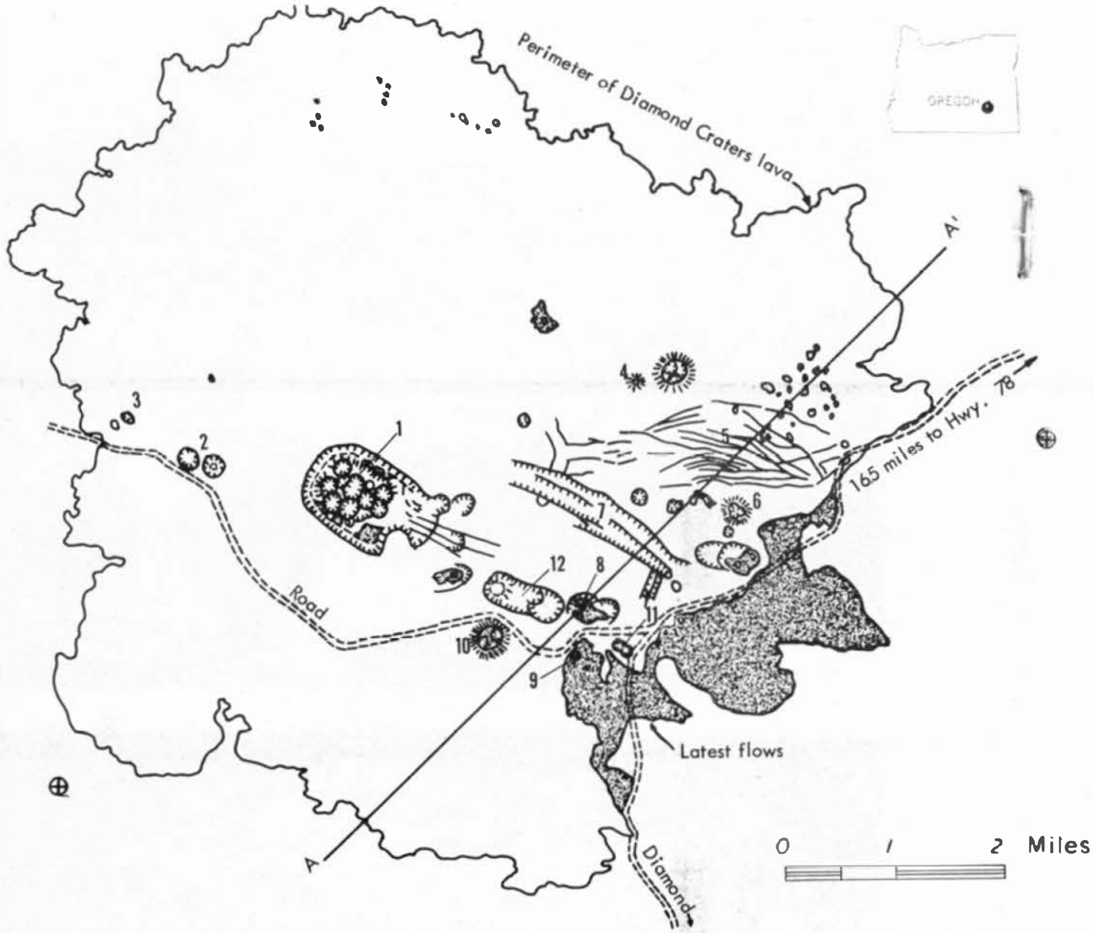
D. Another surge of magma, this on the eastern edge of the area, intruded to form another bulge, Graben Dome, now marked by an almost textbook example of a graben (figure 7). The graben appears to have been formed by subsidence when lava broke out at lower elevations and drained away, thereby withdrawing support. The outflow of fluid black lava occurred at many places low on the south and east flanks of the rising dome. Lava rose within some of the older explosion craters and formed small pools of lava in the crater bottoms. Before the lava pools had cooled, drainage occurred within the conduit, leaving round, steep-walled pit craters with floors of jumbled, thin black lava crusts such as Keyhole Crater (figure 8) and Lava Pit Crater (figure 9). Over other vents small spatter cones were built. Fluid lava from half a dozen sources joined to fill depressions and cover another $1\frac{1}{2}$ square miles (stippled area on index map). The exposed surfaces are glassy and show the ropy texture and collapsed crustal features so common on thin pahoehoe flows.

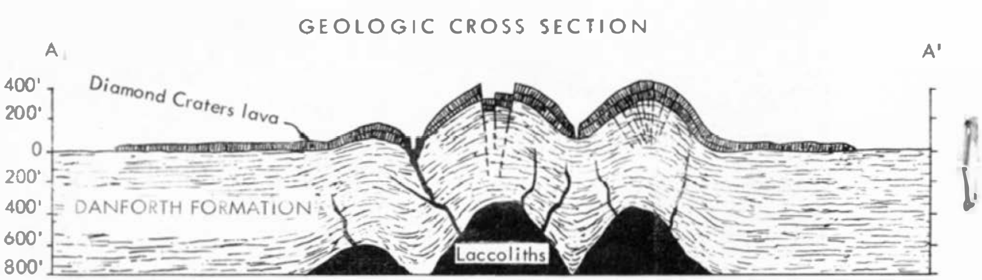
E. Intruding magma next manifested itself to the northeast of Graben Dome and formed Northeast Dome, the western end of which joins Graben Dome. As the brittle lava overlying the Northeast Dome was bowed upward, tension caused fractures to form the pattern that can be so easily seen from the air (figure 10). On the ground these open fissures are as much as 15 feet wide and 50 feet deep. It appears that the magma which raised up this dome did not break out at the surface to form lava flows, but instead, it is probably now cooling at some depth as a laccolithic mass.

The nature of the underlying Danforth Formation has probably made it possible for these domes to form in the Diamond Craters. Magma rising from a fissure could move laterally between the incompetent claystone and


Fig. 5


Fig. 6





Feature	Name		
1.	Central Crater Complex	7.	Graben Dome
2.	Twin Craters	8.	Keyhole Crater
3.	Molheur Maar	9.	Lava Pit Crater
4.	Little Red Cone	10.	Red Bomb Crater
5.	Northeast Dome	11.	Big Bomb Crater
6.	Cloverleaf Crater	12.	Oval Crater

Plate 1. Index map and aerial photograph of Diamond Craters, Oregon.

Fig. 7

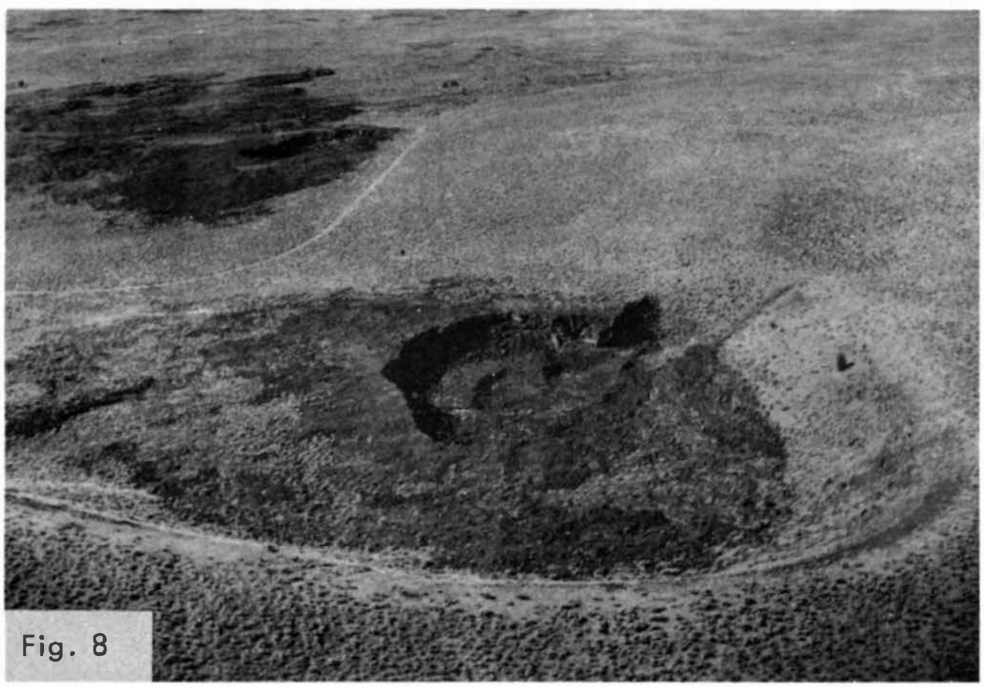


Fig. 8

Figure 7. Looking west along the crest of Graben Dome. Shown is the graben that developed as a collapse feature when the magma which domed up the lava surface broke out at lower elevations to the south and west, withdrawing support. The graben is well developed for 7,000 feet and averages about 1,250 feet in width. Displacement of the down-dropped block is as much as 100 feet. Two accessory grabens cross the main graben at nearly right angles.

Figure 8. Keyhole Crater. The inner, steep-walled pit in stark, black lava is about 400 feet in diameter and 100 feet deep. Fluid basalt welled up to form a lava lake that filled the floor of an existing broad explosion crater. Then the magma column above the vent drained through some subterranean channelway and the thin crust collapsed to form the steep-walled pit. Part of the west wall of hardened basalt was carried back down the vent. Lava benches show that drainage of the lava was intermittent.

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sandstone layers and remain confined at depth except for that portion extruded to the surface by various conduits. The geologic cross-section (plate 1) shows the general relationship of the laccolithic masses believed to underlie the domes.

F. Still later sporadic volcanic eruptions produced features such as Little Red Cone (figure 11), which looks almost as though it were formed yesterday. Volcanism and magmatic intrusion in the Diamond Craters are now presumed to be dormant. No fumarolic activity or hot springs are known to exist.

Cored bombs

The crater rims, floors, and even the debris-covered flat areas near the explosion craters commonly contain unusual spherical to ellipsoidal cored volcanic bombs. They range from the size of a pea to as much as 2 feet in diameter. Most of them are made up of accretionary layers of black or reddish lava surrounding an angular accidental rock fragment. Siltstone, diatomite (?), sandstone, welded tuff, and a variety of other volcanic fragments are all present as cores. These xenoliths have been thermally metamorphosed. In some of the bombs, the lake-bed stiltstone fragments have been burned to a reddish color, the sandstone has been sintered, and welded tuff fragments have been partially to completely melted to a frothy glass. The more basic lava fragments show a lesser degree of alteration.

The origin of these interesting bombs is not completely known, but they probably began as rock fragments which were broken from the walls of the conduit, coated with lava, and carried through the vent into the air by the exploding gases and steam, only to fall or roll back into the vent from which


Fig. 9

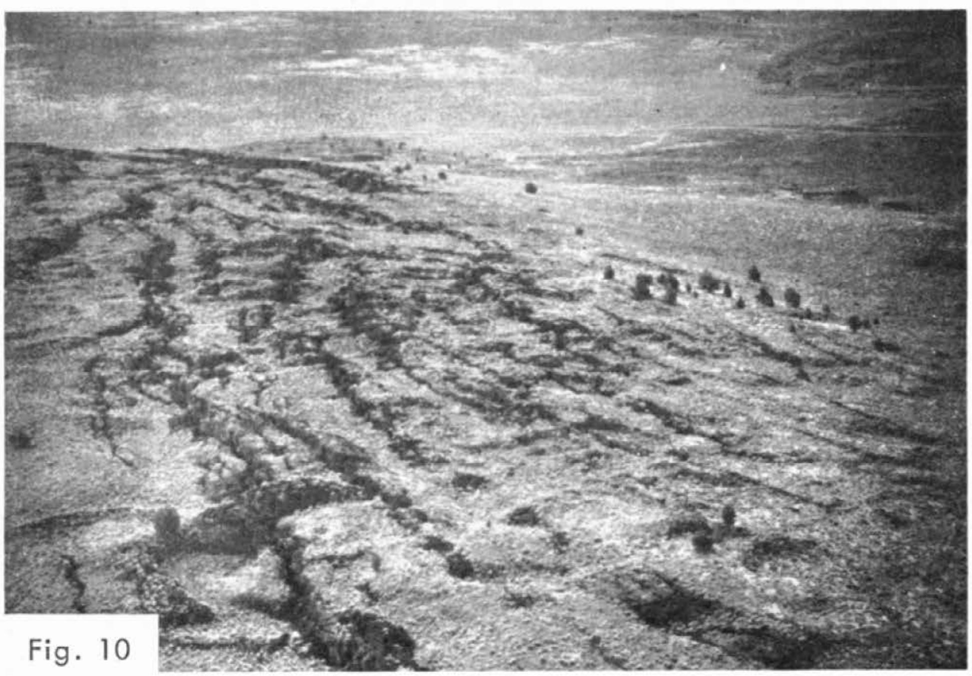
Fig. 10

Figure 9. Lava Pit Crater. This feature is so similar to the small basaltic shield volcanoes with summit pits of Iceland that it could probably be called a miniature shield volcano. Lava welled up slowly on a gently sloping surface. As it overflowed, small lava-tube distributaries carried off the lava in all directions to build up the low, broad dome that is typical of the larger shield volcanoes. Then, just as at Keyhole Crater, drainage of the lava resulted in collapse over the vent to form this steep-walled pit.

Figure 10. Looking eastward along the crest of Northeast Dome, showing the jagged fractures opened by tension as a rising magma domed an area more than a mile long and 3/4 mile wide. Like glacier crevasses, these open cracks are hazards to travel. Some of the largest cracks are 15 feet wide, 40 to 50 feet deep, and extend for long distances. There is no apparent displacement of the basalt walls on either side of the cracks, indicating that little or no subsidence has taken place at the dome crest.

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they came. With further churning in the vent, these fragments received another coating of lava, were thrown out again when a more violent blast occurred, and finally, after repeated activity, came to rest on the rim of the crater. Such a combination of processes is probably responsible for the smooth, rounded shape of most of these unusual bombs.

A further, more detailed study of the composition and texture of the accretionary coatings and cores is being made in order to determine more details about their origin. Figures 12a and 12b show a group of typical, cored bombs from various crater rims in the Diamond Craters area.

Conclusion

Diamond Craters lie in an isolated recent volcanic field at the southern edge of Harney Basin. The nearest recent volcanic areas are the Four Craters Lava Field about 100 miles to the west and the Jordan Craters about 60 miles to the east. Diamond Craters present many unusual features that exist at no other recent volcanic areas in Oregon. Three of these features stand out above the rest for special interest. One is the Central Crater Complex, for which one can neither give a simple explanation of its origin nor provide a simple description of its physical characteristics. A second unique feature is the graben at Graben Dome, which can be examined as though it were a model for classroom study, since almost no detail has been destroyed by weathering and erosion. Lastly, the system of fissures on Northeast Dome, a multitude of gaping cracks, provides an outstanding example of what happens to a brittle sheet of lava when it is rapidly warped upward. These structures, along with the many other recent volcanic forms, provide variety to anyone interested in delving into the processes of volcanism

Fig. 11

Fig. 12a

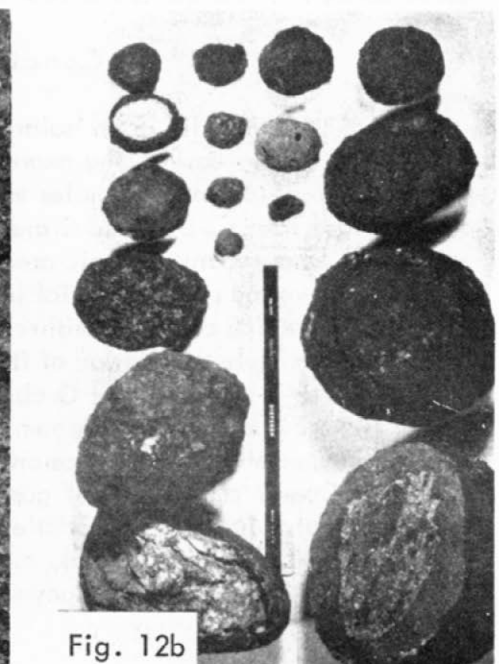

Fig. 12b

Figure 11. Little Red Cone. This small cinder cone, only 250 feet in diameter and less than 75 feet high, has smoothly rounded rims of reddish cinders and scoria. It was born of one of the most recent explosive eruptions at Diamond Craters and is one of the least eroded features in the area. Partly obliterated older craters show that Little Red Cone is built over a vent that has a history of explosive eruption.

Figure 12. Cored bombs. a) A variety of the peculiar and interesting cored bombs from a crater rim within the large Central Crater Complex. Fragments of shale, mud, welded tuff, and basalt are the most common cores that have been encased in concentric layers of black and red lava. b) An assortment of sizes and shapes of cored bombs. These objects can range from the size of a pea to 3 feet in diameter. Most are round or oval, but some are merely lava-coated angular fragments.

Another aspect of the Diamond Craters which deserves further investigation is their possible potential for the development of geothermal energy. Since the most probable cause for the domes is the formation of small laccoliths, these may be at a moderate depth, perhaps no more than a few hundred feet below the surface. The recency of the latest volcanism leads one to believe that considerable heat may still exist in these intrusive bodies and surrounding rock, even though no fumarolic activity or hot springs are known in the area. Geophysical exploration might confirm the presence of these intrusives and determine their approximate depth. If conditions were found to be favorable, the drilling of a test hole could prove the existence of steam or superheated water at depth. Engineering studies on the amounts of steam and/or superheated water which could be produced, its temperature and pressure, corrosiveness, and other properties would then determine the commercial feasibility of generating power.

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