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GEOLOGY OF CRATERS OF THE MOON NATIONAL
MONUMENT, IDAHO

A Thesis

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by

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BIOGRAPHICAL SKETCH OF THE AUTHOR

John Graham Murtaugh was born in Mineola, New York on December 12th, 1934. He graduated from Flushing High School, Flushing, New York in 1952. He then worked as traffic clerk for two years before entering Miami University at Oxford, Ohio. He volunteered for the draft and entered the U. S. Army in 1955 after completing his sophomore year. Upon leaving the Army in 1957 he entered the University of Dayton, Dayton, Ohio. He graduated in 1959 with a Bachelor of Science degree in Geology. He then accepted a Teaching Assistantship at the University of Idaho, where he fulfilled the requirements for a Master of Science degree in Geology.

ABSTRACT

The Craters of the Moon National Monument, Idaho is an area of Quaternary basaltic flows representing the latest phase of the volcanic eruptions of the Snake River Plain. These rocks overlie folded Oligocene quartz latite vitrophyres and basaltic vitrophyres, and Miocene quartz monzonites.

Most of the basaltic flows issued from vents in the Great Rift Zone, a northwest-trending, elongate area of weakness in the crust that is parallel to fold axes in the older rocks. There may have been four periods of eruption, but a significant time interval existed only between the first period and the later periods.

The primary vent structures include cinder cones, spatter cones, spatter ramparts, and lava domes. Spindle, ribbon and breadcrust bombs are common. Cow-dung bombs are rare.

The rootless vents which are those not directly connected to the magma conduit, formed over cracks in the surfaces of some flows. Secondary lava domes are formed by pahoehoe flow units that have broken through the roofs of lava tubes. Hornitos are cones of spatter formed over rootless vents.

More than fifty flows were recognized in the Monument. They are mostly pahoehoe and aa, with a few block lava flows.

The pahoehoe is basalt with a generally smooth crust that may be corded and festooned. Lava tubes as much as sixty feet in diameter are exposed by collapse. Pressure ridges are

common. Squeeze-ups have broken through the crust, in places flowing out and forming flow units. Squeeze-outs of pahoehoe have broken through the margins of aa flows, in places becoming flow units.

The aa is basalt with a jagged, spinose surface, and a central massive layer. Open channels braid the surfaces of some aa flows.

The block lava flows are andesitic basalt. They are composed mostly of smooth, angular, discrete blocks, that may be mixed with aa.

Monoliths found in the Monument are fragments of cinder cones that have been carried by some of the thick flows. Grooved lava occurs where plastic lava has been rubbed by hard surfaces. Xenoliths are fragments of pyroxene granulite that have been carried up from depth by the basaltic magma.

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GEOLOGY OF CRATERS OF THE MOON NATIONAL
MONUMENT, IDAHO

BY

JOHN GRAHAM MURTAUGH

INTRODUCTION

PURPOSE AND SCOPE

The main purpose of the investigation was to determine the relative ages of the various flows and make a geologic map of the Monument. The sources of the different flows were determined, where possible, and the various extrusive units described. The pre-Snake River Basalt rocks were mapped. Special features associated with the flows were described. A petrographic description of the various rocks, including the xenoliths in the basalt, was given.

Time did not permit detailed mapping of the entire Monument. As a result, most of the report deals with the north part of the Monument and only a brief description is given of the south part. An attempt is made to avoid duplication of previous written material. Therefore, detailed descriptions of the individual cones and lava tubes are not given because they have been described by Stearns (1926). Emphasis is placed on a general description of the volcanic phenomena in an effect to aid members of the Park Service who must interpret these features to the public. The general description of the features is patterned in large part after Wentworth and

Macdonald (1953) because features similar to those found in the Monument have been described by them from Hawaii. The geologic map is intended to be supplemented by the topographic map of the Monument published by the U. S. Geological Survey.

GEOGRAPHY

The Craters of the Moon National Monument covers an area of about 80 square miles in Butte and Blaine Counties, on the north side of the northeastern part of the Snake River Plain (fig. 1). It is about 18 miles southwest of Arco on U. S. Alternate Highway 93. The elevation changes from about 5350 feet in the southwest part of the Monument to 5950 feet at the base of the Pioneer Mountains where there is a sharp increase in elevation to 7688 feet, the highest point in the mountains in the Monument.

The climate is semi-arid. Measurements of the precipitation at the Monument have begun only recently. Weather reports for Arco record an annual precipitation of about ten inches. The mean annual temperature in Arco is about forty degrees. The climate at the Monument is similar to that at Arco except that less rain falls on the Monument in the summer months, especially in the part of the Monument that is part of the Snake River Plain. Most of the precipitation occurs in the winter months, in the form of snow. The prevailing winds are from the southwest. Stearns (1926?) gave a detailed description of the climate, and recent reports on the climate are

contained in the files of the Park Service at the Monument.

The vegetation is sparse, except on a few flows, Sagebrush, rabbitbrush and limber pine are common. Many of the flows appear bare, but close inspection reveals various types of plants growing in loess and ash in the crevices. A detailed description of the flora has been written by Marie McElreath in Stearns (1928).

FIELD AND LABORATORY PROCEDURES

Most of the material presented in this report is based on field work done during a period of about three months from June to September, 1960. The boundaries of the flows were mapped on the topographic map of the Monument with the aid of air photos and field observations. Flow contacts were walked out in as many areas as possible and the stratigraphic relations determined. Most of the time was spent mapping the flows in the north part of the Monument.

A general petrographic study was made of specimens collected in the field. Most of the thin sections studied were of basalt from the flows in the north part of the Monument.

PREVIOUS WORK

A detailed description of the early geology and exploration is given by Stearns (1926?). Only a brief sketch is presented here, of the work of those who have contributed significantly to the geology and exploration of the Monument.

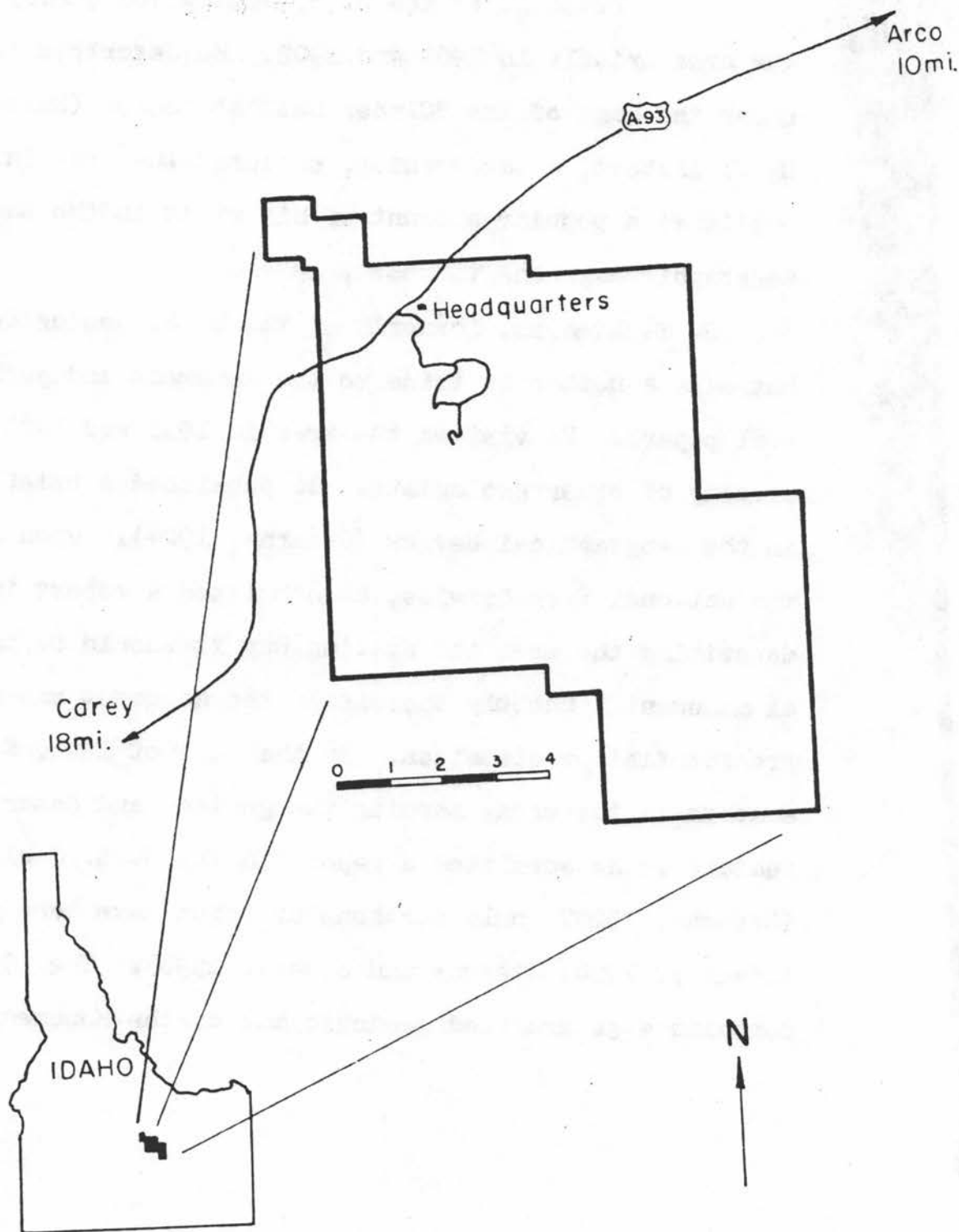


Fig.1- INDEX MAP SHOWING THE LOCATION OF
CRATERS OF THE MOON NATIONAL
MONUMENT.

I. C. Russell, of the U. S. Geological Survey, studied the area briefly in 1901 and 1902. He described the area under the name of the "Cinder Buttes" region (Russell, 1902). R. W. Limbert, a taxidermist, explored the area in 1921 and published a popular account of his visit in the National Geographic Magazine (Limbert, 1924).

H. T. Stearns, formerly of the U. S. Geological Survey, has made a number of trips to the Monument and published several papers. He visited the area in 1921 and 1923 in the company of other geologists. He published a brief description in the Geographical Review (Stearns, 1924). Upon request of the National Park Service, he submitted a report in 1924 describing the area and stating why it should be made a national monument. Shortly thereafter the Monument was created by Presidential proclamation. In the fall of 1926, Stearns spent a month in the area, mapping the geology and describing the features. He submitted a report to the U. S. Geological Survey (Stearns, 1926?) only portions of which have been published (Stearns, 1928; Stearns and others, 1938). The 1938 publication contains a generalized geologic map of the Monument.

ACKNOWLEDGMENTS

The National Park Service provided the funds necessary to undertake and complete this project. The U. S. Geological Survey released an unpublished report on the Monument which helped make this report better.

The employees of the National Park Service at the Craters of the Moon National Monument cooperated to aid the field work in a friendly and willing manner. Special thanks are due to the following employees of the Park Service: Peter G. Sanchez, Seasonal Ranger-Naturalist and geology student from the University of Utah, who made many helpful suggestions based on his knowledge of the geology of the area; David C. Ochsner, Park Naturalist, who provided transportation whenever necessary and accompanied me on a number of field trips; and Floyd A. Henderson, Park Superintendent, who made suggestions based on his experience in Hawaii.

Dr. Rolland R. Reid, Head, Department of Geology and Geography, University of Idaho, the author's major professor, made several suggestions in the field, aided in the petrographic examination, and supervised the preparation of the manuscript.

Ray Wilcox of the U. S. Geological Survey, during a visit to the area, made several helpful suggestions on the interpretation of the geology.

REGIONAL GEOLOGY

GENERAL

The brief description that follows, of the geologic events preceding the Quaternary eruptions in the Craters of the Moon National Monument, is based mostly on the work of previous authors. The general description of events in the Snake River Plain area is after Ross and Forrester (1958). The specific description of the geology of the Pioneer Mountains is mostly after Anderson (1929a). The reader is referred to these authors for detailed descriptions.

Investigation of the geology of the Tertiary rocks constituting the Pioneer Mountains in the northwest part of the Monument was not considered vital to this report. As a result, the writer spent only a few days in that area, and the description of these rocks, as well as that of the Recent alluvium at the base of the mountains, is included in the following section.

GEOLOGIC HISTORY

The earliest event recorded in the rocks in the immediate vicinity of the Monument was the deposition of thick beds of limestone, shale and sandstone, in Mississippian time. Older sedimentary rocks are exposed in areas farther north and west. The next period of deposition for which there is evidence was in Oligocene time. During much of the intervening time, sedimentation was taking place in other parts of southeast Idaho.

The Mississippian rocks were folded near the close of Mesozoic time. Anderson (1929a, p. 26) stated that these folds trend generally northwest.

Uplift in late Mesozoic and early Tertiary time was followed by erosion that carved valleys in the Mississippian sedimentary rocks. The valleys were filled and the hills buried in late Oligocene or early Miocene time by the Challis Volcanics. Granitic stocks were intruded in middle or late Miocene time. The single stock within the Monument cuts the Challis Volcanics.

The Challis Volcanics within the Monument were determined to be quartz latite and basaltic vitrophyres. The stock ranges in composition from quartz monzonitic to grandioritic. A complete description is in the section on petrography. Anderson (1929a) gave a detailed description of all the rocks in the Pioneer Mountains.

Folding, faulting and jointing of the Challis Volcanics accompanied the intrusion. Anderson (1929a, p. 26) reported that the folds trend approximately northwest and are sub-parallel to the late Mesozoic folds.

Extensive mineralization took place both during and after the intrusion. The ore deposits of the Lava Creek district were formed at this time, including the deposit in the Martin mine in the Monument. According to Anderson (1929a), the ore in the Martin mine is in a pipe-shaped body where the stock was extensively altered to clay along a zone of intersecting

fissures. Pyrite, galena and sphalerite are the dominant minerals. Gold and silver are the valuable metals. The only significant shipping of ore was in the 1920's. The value of the ore shipped at this time was about \$22,000. Anderson (1929a, p. 59) gave a detailed description of the ore body and the mine.

The Columbia River basalt flows were being extruded in the western part of the state at about the time of the intrusive activity described above. Shortly thereafter, and perhaps concurrently, the structural basin of the Snake River Plain was being formed throughout much of southern Idaho. The formation of this great structural basin may be due either to downwarping or faulting or both.

The youngest Tertiary volcanics erupted in the Snake River Plain structural basin were rhyolitic in composition. The rhyolitic rocks crop out mostly along the south border of the plain. Most of the later eruptions were of extensive basalt flows. These were primarily fissure eruptions from gently sloping lava domes. At this time the Tertiary volcanics and intrusives in the north part of the Monument were being eroded.

The valley floor at the mouth of Little Cottonwood Creek was being filled by a small alluvial fan that may have abutted against the basalts of the Snake River Plain.

The Snake River basalt flows extend up to the base of the mountains in areas adjacent to the Monument. The building of alluvial fans has been continuous; gravel, composed of angular

and subangular fragments of Tertiary volcanics and intrusives, overlies the old flows in the Monument north of Sunset Cone and Grassy Cone.

A layer of basalt cinders about two feet thick crops out in a few places in the valley of Little Cottonwood Creek. The cinder layer is interbedded with the alluvial cover. The source for the cinders was not determined, although they are probably a product of the early eruptions in the Monument.

Volcanic activity became localized along the Great Rift Zone, probably during Pleistocene time. The Great Rift Zone is a narrow band of northwest-trending parallel fissures and cinder cones. The trend of this fissure zone is thus parallel to the axes of the Mesozoic and Miocene folds. The Great Rift Zone extends for at least sixteen miles southeast from the foot of the Pioneer Mountains.

However, the Great Rift Zone is not restricted to the Snake River Plain. Two cinder cones have formed on top of two peaks in the Pioneer Mountains. These cones have been described in detail by Anderson (1929b). They are called South Vent and North Vent and are located $4\frac{1}{2}$ and 6 miles, respectively, in a line northwest from the apparent termination of the Great Rift Zone at the foot of the Pioneer Mountains. An aa flow from South Vent has advanced down the south fork of Lava Creek. This aa flow overlies the Snake River Plain flows and appears to be much younger. Anderson (1929b, p. 13), believed that these vents are on an extension of the Great Rift Zone and that

they erupted about the same time as the earliest flows in the Monument.

GEOLOGIC HISTORY OF THE CRATERS OF THE MOON

GENERAL

The sequence of events described in the geologic history given below may be subject to considerable correction as a result of future research. The interpretation is based on reconnaissance geology and not detailed field mapping. The relative age relations were determined almost entirely on the basis of surface and near-surface contacts, because very few cross-sections exist.

Stearns (1926? and 1928) has written a geologic history and listed an approximate sequence of eruption of the flows. He has also published a geologic map (Stearns and others, 1938, plate 13). The author disagrees with parts of Stearns' interpretation of the relative ages of the flows, but no attempt is made here to give a detailed accounting of the differences of opinion. The reader is invited to compare the interpretation with that of Stearns.

The eruptions are grouped into several periods, partly for convenience in description, and partly because the possibility exists that there may be significant time intervals between some of the periods. There may be four periods of eruption, but a significant time break is indicated only

between the old red-topped flows and the more recent black and gray ones. Stearns (1926? and 1928) recognized three periods of eruption and made note of the fact that most of the flows were part of a generally continuous sequence.

No attempt is made to list the flows in a numerical sequence from oldest to youngest. Correlation between overlapping flows was done locally with some degree of accuracy, but correlation over wide areas was impossible. Flows that are widely separated are grouped according to degree of weathering, cinder cover, and, in some cases, the kind of flow. These criteria are indefinite at best. The stratigraphic relations between flows in local areas are given in the section on the description of the flows. A stratigraphic chart of some of the flows is given in Table 1.

ABSOLUTE AGE DATING

Stearns (1926?, p. 294-308) gave a detailed description and criticism of the various methods that have been used to determine the absolute ages of the flows. The discussion here is limited to a brief mention of two methods that have been used since the time of Stearns' report. Correspondence pertaining to the studies described here is on file with the National Park Service.

A boring was made a few years ago of a limber pine growing on one of the most recent flows in the Monument. Dendrologists at the University of Arizona determined that the tree was about

1350 years old.

Scientists at the University of California are in the process of determining the age of a number of the flows by the process of thermoluminescence. No results have been reported yet.

SEQUENCE OF EVENTS

The only vestiges of the oldest volcanic activity in the Monument are the shattered remnants of ancient cones and possibly a few of the still intact cones that stand as kipukas in younger flows. These cones probably formed in Pleistocene time. The chain of cone remnants near the west boundary of the Monument and the disrupted cone that once occupied the site of the campgrounds and the Park Service headquarters may be of this age. Round Knoll, a cinder cone northeast of the Great Rift Zone, with its deeply weathered bombs and cinders may be even older.

Some of the pahoehoe flow surfaces have been weathered red by oxidation. The flows with red surfaces are almost completely covered with layers of cinder and loess. These flows support a thick growth of sagebrush. Flows from Sunset Cone, Grassy Cone, and Echo Crater?, as well as the unnamed flow(s?) 15 have a similar surface. These flows and the cones they issued from may be either of the same age as the disrupted cones discussed above or slightly younger. Silent Cone and Fissure Butte may have formed during this first period of eruption. Parts of Big Cinder Butte, Inferno Cone and Paisley Cone are made up of fragments of old red cinder that have been almost completely covered by cinder and ash from later eruptions. The older parts of these cones formed during

the first period of eruption.

The red-topped pahoehoe flows described above appear to be intermediate in age between the Pliocene basalt of the Snake River Plain and the younger flows that cover most of the Monument. The interval following the extrusion of the red-topped flows appears to be the only significant gap in the sequence of eruption.

The early part of the second period of eruption appears to have been dominated by the eruption of thick block lava flows and massive pahoehoe flows. The Devil's Orchard flow was probably the first to be extruded, followed closely by the Serrate and Serrate? flows, and perhaps, the unnamed flow 9 southwest of Big Cinder Butte. The Highway and Black flows were extruded, as well as the pahoehoe and aa flows from The Sentinel. The Derelict and Sawtooth flows may have been extruded next or perhaps somewhat earlier. Broken Top, Half Cone, Crescent Butte, Split Butte, The Watchman, part of North Crater and most of Big Cinder Butte may have been formed during the second period of eruption. The unnamed flow 1 may be either one of the last flows erupted in this period or one of the first in the next period. No significant time interval is apparent between the extrusion of the flows just described and those described below.

The vents that issued the flows in the third period of eruption are mostly elongate fissure zones. Some of the fissures have split open older cinder cones whereas others have

built chains of spatter cones, spatter ramparts and elongate, multicratered cinder cones.

In the north part of the Monument the first event in the third period of eruption was probably the extrusion of the Big Craters Northeast and Northwest flows, followed shortly by the eruption of the Registration Waterhole flow. The unnamed flow 2, which may actually be the Big Craters Northwest flow, was erupted. The vent at Big Sink erupted during the third period, but the flows from this vent are now completely buried. The lava dome at Lava Cascades formed, extruded lava and collapsed. Broken Top was faulted, and the Buffalo Caves flow and the unnamed flows 6 and 7 were erupted from the resulting fissures. The unnamed flow 5 was extruded at about the same time. The flow, or flows, comprising the Lava Dome Complex were extruded next. Then the Big Craters Southwest flow and the Crystal Fissure flow were extruded.

In the south part of the Monument, the first event in the third period of eruption may have been the extrusion of the Trench Mortar Flat flow. Fissures split the cone called The Watchman and the area to the north of it, issuing a number of short flows and the Little Prairie Aa flow. Sheep Trail Butte was formed, erupting at several different times, during this period. Fissure Butte was split open and at least one flow issued from the vent that formed. The small flow from the spatter cones on the saddle between Sheep Trail Butte and Fissure Butte, may have been formed concurrently. Vermilion

North Crater flow, Big Cinder Butte Northeast flow,
Cave Dome flow, Blue Dragon flow

Big Craters Southwest flow, Crystal Fissure flow

Lava Dome Complex flow(s?)

Lava Cascades flow

Unnamed flow 2

Big Craters Northwest flow

Buffalo Caves flow

Unnamed flow 1

Trench Mortar Flat flow

Serrate flow, Serrate? flows

Black flow

Devil's Orchard flow

Highway flow

Sunset Cone flows, Grassy Cone flow

Table 1

Stratigraphic chart showing relative age relations of certain flows in the north part of the Monument. The oldest flows are at the bottom of the chart. Dashed lines separate inferred periods of eruption.

Chasm and the fissures extending southeast from it may have been formed during the third period of eruption or may be earlier.

Several flows of "Blue Dragon" pahoehoe are the most recent in the Monument. Because there is no contact between these flows, it could not be determined whether or not they are contemporaneous. They may have issued during the fourth period of eruption or they may have issued at different times shortly after the flows that each overlies. They all overlie flows that are among the most recent in the Monument. The North Crater, Cave and Blue Dragon flows are part of this group. The Big Cinder Butte Northeast flow and the unnamed "Blue Dragon" flow 7 east of Broken Top also appear to be part of the last period of eruption.

VOLCANIC EJECTA

GENERAL

Volcanic ejecta are solidified clots of magma that were projected into the air by explosive activity at a vent during an eruption. The explosive activity is caused primarily by the expansion and liberation of gas as the magma arrives at the surface. Ejecta range widely in size and shape. Some types cool and solidify entirely or partly while in flight and others are still plastic or fluid upon striking the ground. A more detailed description may be read in Wentworth and Macdonald (1953). Stearns (1928) described and showed photographs of

some of the ejecta in the Monument.

ASH

Volcanic ash is the term used to describe particles less than 4 millimeters in diameter. The color of these particles is black, brown, or red. Ash cools rapidly owing to its small size and is solid upon striking the ground. The thickest ash layers occur near vents but thinner layers may be spread over a wide area because ash particles are carried easily by the wind.

CINDER

Cinder ranges in size from about a $\frac{1}{4}$ inch to several inches in diameter. The particles are generally pumiceous in texture, with many large vesicles. The color is black, brown or red. The surface of many cinders is iridescent. Cinders are solid upon striking the ground. Most cinder falls near vents although some is carried over a wider area by the wind.

BOMBS

Volcanic bombs in the Monument range in size from $\frac{1}{4}$ inch to 13 feet. Most of the bombs attain a final shape while in flight although some are modified by impact with the ground. The color of the bombs may be black, red, or yellow. Some bombs are dense whereas others are abundantly vesicular. Bombs fall near vents, on top of the cinders or the adjacent flows. They are apparently ejected mostly during the waning phase of an eruption.

Breadcrust bombs are characterized by a checked structure on the outer surface, resembling the crust of a loaf of bread. The checking probably results from the rapid cooling of a thin layer of the outer surface, which contracts and cracks. Breadcrust bombs are all at least a foot in diameter, and may be as large as several feet. They tend to be spherical in shape and are abundantly vesicular. The vesicles are largest in the center of the bomb and decrease in size outward. Fragments are found more commonly than whole bombs, probably because the breadcrust bombs are solid upon landing but weak because of their high vesicularity. Breadcrust structure also occurs on a few of the larger spindle and ribbon bombs described below.

Spindle bombs are of spindle or fusiform shape. Most of them are dense and heavy with generally small vesicles. They range from an inch to 8 feet in length. One side is typically smooth and the other ribbed. Wentworth and Macdonald (1953, p. 81) believed that the fusiform shape is due to surface tension and that the ribbed and smooth sides are produced by air drag. Detachment from a parent mass of lava at both ends may be the cause of the ears or tails that are characteristic of this type of bomb. Spindle bombs are generally solid upon landing although one specimen on the northwest slope of Big Cinder Butte was still somewhat plastic, and bent into an "S" shape upon landing (fig. 2).

Flattened, elongate ribbon bombs range from a fraction of

an inch to a foot and a half in width. They apparently result from the pulling apart of two clots of lava, and many are probably the tails of spindle bombs that broke off, either in flight or upon landing. The largest bomb reported in the Monument was a ribbon bomb thirteen feet long (Stearns 1928, p. 29).

Cow-dung or pancake bombs are partly viscous at the end of their flight and assume their characteristic shape by flattening out upon landing. This type of bomb is not common in the Monument. Only one cinder cone has abundant cow-dung bombs. This is Round Knoll, which is an ancient cone outside the Great Rift Zone. Some bombs on Round Knoll are red, but many have been weathered yellow. Cow-dung bombs grade into spatter with increasing fluidity of the ejected lava.

SPATTER

Spatter is made up of clots of very fluid lava that travel only a short distance from the vent. The spatter clot is deformed upon impact and may flow or ooze for a short distance. Agglutinate is the term applied by Wentworth and Macdonald (1953, p. 27) to masses of spatter that have welded together as a result of this flowing action.

PRIMARY VENTS AND THEIR STRUCTURES

GENERAL

The primary vents that were the source of the lava flows

in the Craters of the Moon mostly appear to have been fissures. The magma that worked its way up from the chambers at depth poured out on the surface from these narrow, elongate openings. Most of the vents are either bordered or covered completely by volcanic ejecta or flows. The following sections contain a description of the features that have been formed at these vents. The reader is referred to Wentworth and Macdonald (1953) for additional description of basaltic vents and their structures.

CINDER CONES

Cinder and ash are commonly ejected from the vents that issue basalt flows. The explosive activity of basaltic magma is relatively mild and most of the cinder and ash fall near the vents. Eventually large mounds of cinder and ash are built up. The sides of the mounds have an average slope of about thirty degrees. In plan view the mounds are roughly circular. The general effect is that of cones of cinders, although ash is an important constituent and bombs may dot the surfaces. Short flow units of lava are often interbedded with the cinders, adding to the constructional strength. The surfaces of the cones are generally indented with craters. These craters were in some cases the location of a pool of lava and in others merely the site of a transitory lava fountain spewing ejecta. Many of the craters are breached where the upwelling lava broke through the sides of the cones.

The true height of many of the cinder cones cannot be determined because the cones have been partially buried by later flows. The cinder cones range in height from about 50 to 800 feet. Most of them are in the Great Rift Zone but a few are outside. Stearns (1926?) described the individual cones, and also (Stearns 1928, p. 54) gave a list of locations and heights.

Some of the cones were formed during at least two different eruptions. The color of the ejecta changes from black to red either at different levels or in different parts of some of the cones. This color change may be due to more violent fountaining activity in places and consequent greater oxidation of the ejecta. The oxidation and red color may also be due to greater age.

SPATTER CONES AND SPATTER RAMPARTS

Spatter ejected from a vent travels only a very short distance in the air. Steep-walled accumulations of welded spatter or agglutinate form around the vent. The spatter may either accumulate around a circular vent and form a spatter cone (fig. 3) or it may accumulate as spatter ramparts bordering an elongate fissure (fig. 4). The vent is generally exposed either between the ramparts, or in the spatter cones, as a central orifice. Fumarolic activity may color the lava yellow and orange near the vent, but this type of gaseous activity was present only in a few places in the Monument.

PRIMARY LAVA DOMES

The term lava dome as used herein is synonymous with lava cone as defined by Wentworth and Macdonald (1953, p.6-8). Dome was the term used by Stearns (1926? and 1928). The word dome is most descriptive of these gently sloping features. Cone is better restricted to those features which have a steep slope.

Lava domes are made up of a number of flows or flow units that have issued quietly from a vent. Little or no ejecta are associated with the domes. The sides slope gently, generally at an angle of less than 5° . The domes may collapse when the lava drains out at the end of an eruption. Lava Cascades and Big Sink are examples (fig. 5).

Lava domes dot the Snake River Plain outside the Monument and were the sources of the extensive basalt flows on the Plain. They have erupted both pahoehoe and aa flows, although pahoehoe predominates.

ROOTLESS VENTS AND THEIR STRUCTURES

GENERAL

Rootless vents were defined by Wentworth and Macdonald (1953, p. 26) as those vents that are not directly associated with the conduits that bring magma to the surface from the magma chambers. One of the types of rootless vent that they described was caused by a lava flow entering a pre-existing tube or tubes and then flowing in the tube or tubes for a

distance before breaking through to the surface at a place remote from the original vent. This process may have occurred at Great Owl Cavern.

Flow units may break out from a tube or pressure ridge. In this case the new flow unit comes from the same source as the pre-existing flow and is, in fact, the same flow. The mechanism is discussed in the section on pahoehoe flows. Later flow units may completely cover the earlier part of the flow, thus making it impossible to determine if the vents are primary or rootless.

SECONDARY LAVA DOMES

The physical description of secondary lava domes is the same as that for primary lava domes. The difference is in the source of the lava. The Great Owl Cavern Dome, previously mentioned, may be secondary. Some of the domes east of Inferno Cone may be of this type. The secondary lava domes are all comprised of many small flow units dipping gently out from a central area that is about 20 to 30 feet higher than the surrounding terrain. They may be caused by lava breaking out of large tubes at weak points in the flow crust.

HORNITOS

Hornito is the term applied to a "spatter cone" formed over a rootless vent. Hornitos may occur where the crust of a flow has broken, allowing the fluid lava underneath to

spatter out (fig. 6). Hornitos may also occur over lava tubes. The two hornitos west of Needles Cave dome may have formed over a lava tube.

FEATURES OF LAVA FLOWS

GENERAL

The lava flows in the Monument are basaltic. They are fine grained and vesicular. The minerals are too small to be seen either with the naked eye or a hand lens, though phenocrysts occur rarely. Fresh, broken surfaces are black. Some flow surfaces are grey because of weathering. Others are an iridescent blue and (rarely) gold. The cause of the iridescence has not been determined. Some parts of the flows are red or red-brown owing to oxidation by gases at the time of eruption.

Three types of basaltic lava are present in the Craters of the Moon. They are pahoehoe, aa, and block lava. Wentworth and Macdonald (1953, p. 32) described the first two as follows: "Pahoehoe may be defined as the variety typified by a smooth, billowy, or ropy surface, and aa as that typified by a rough, jagged, spinose, clinkery surface." Block lava is fragmental like aa, but the blocks are smooth and angular. Some of the block lava flow units are comprised entirely of discrete blocks. Only the surface and base of aa flows are fragmental.

All three types are intergradational. The change in the physical character of the flows is apparently due to increasing viscosity in the sequence from pahoehoe to aa to block lava. The increasing viscosity is believed to be caused by a loss of gas, a greater degree of crystallization, and, in the case of block lava, by a more silicic composition. Further discussion is beyond the scope of this report. The reader is referred to Macdonald (1953) for a full discussion.

Flows may be as thick as 60 feet or as thin as a foot. The length of the flows in the Monument ranges from a few hundred feet to 4 or 5 miles. Some of the flows continue beyond the boundaries of the Monument. The average gradient of the surface of the flows is about 50 feet to the mile, although a few flows slope at about 200 feet to the mile near the vent.

FLOW UNITS

Flow unit is a term proposed by Nichols (1936) for a tongue-shaped, penecontemporaneous subdivision of a flow. Flow units may form in several ways. Some issue successively from primary vents during the course of an eruption. Others result from fluid lava breaking through weak spots in the hardened crust of a halted or temporarily ponded flow. The latter type may break through the crust either from the flow margin or on the top of the flow.

Multiple flow units are common, and many pahoehoe flows

are aggregates of flow units. Generally the flow unit is the same type of lava as the parent flow, but some flow units of pahoehoe issue from the margins of aa flows.

PAHOEHOE

GENERAL

The pahoehoe flows are basalt. Pahoehoe flows have a generally continuous, relatively smooth crust. The surface is in places flat, ridged, bulbous and humped. Pahoehoe advances through the mechanism of lava tube formation. Tubes form by the crusting-over of channels in the lava. Large tubes near the vent subdivide into small braided tubes as the flow advances. Multiple flow units are common. Individual flows and flow units may be only about a foot thick. Certain flows are more than 150 feet thick.

Unbroken flow tops are generally grey, sometimes black, and, on a few flows, iridescent blue and blue-white. A thin top layer of the crust is broken in places to reveal a smooth-surfaced underlayer. Gas may glaze the top of the underlayer and the bottom of the upper crust, oxidizing both to a yellow-brown or red-brown color. In other places only the underlayer is colored.

Vesicles are abundant near the tops of the flows. They have smoothly curved outlines and are commonly elongate in the direction of movement of the lava. Some vesicles are

spheroidal, and others are stretched into narrow ribbon shapes several inches long. The vesicles decrease in size and abundance toward the center.

TYPES OF PAHOEHOE

Many types of pahoehoe have been recognized by different workers. The names used herein are mostly defined by Wentworth and Macdonald (1953) and Jones (1943). The smaller features may be superimposed on the larger ones.

Minute upright spines about a millimeter in height cover the surface of some flows. These spines are caused by escaping gas bubbles, which pull up the plastic lava. Such spinose lava is called sharkskin pahoehoe. It is common on flows where pahoehoe is changing to aa and on flow units of pahoehoe that have issued from the margins of aa flows. It may be seen on flow units of the west margin of the Serrate? flow and on squeeze-outs from the Crystal Fissure aa flow along the east side of Inferno Cone.

"Toothpaste lava" is pahoehoe with a coarse sharkskin or spinose texture and locally grooved surface. Bullard (1947, p. 444) stated that the term is used locally in Mexico to describe certain flow units of the volcano, Parícutin. Squeeze-outs and flow units of pahoehoe issuing from the margins of aa and block lava flows in the Monument are "toothpaste" lava (fig. 21). Squeeze-outs are described in detail in the following section.

Filamented pahoehoe is the term used to describe surfaces where the spines described in a preceding paragraph have bent back onto the flow surface before solidifying. Filamented pahoehoe is common.

Cord-like ridges, about an inch in diameter, parallel the direction of movement on many of the flows. These ridges are called corded pahoehoe. One typical occurrence is on the pressure ridge east of Inferno Cone along the trail to the cave area.

Festooned pahoehoe occurs when cords or ridges are dragged into festoons, convex in the direction of movement, by the flow of liquid lava under the crust. Festooned ridges range from an inch to three feet in height (figs. 7 and 8). The larger ones are hollow and may break into the slab lava described below. They occur both on level surfaces and, on the sides of pressure ridges, on flow units that have come out of the tops of pressure ridges and flowed down the sides. Large festoons are common on the east portion of the unnamed flow 2. Small festoons are common on many flows. Festoons are not a reliable indicator of the general flow movement. In small areas they are often convex in widely divergent directions. They are local features that form just before the crust solidifies.

Shelly pahoehoe is the term applied to lava that is a complex of hollow, thin crusted tubes and gas blisters, one foot to 3 feet in diameter. These shells are often partly

broken. This type of lava may be seen on the Lava Cascades flow and the unnamed flow 6 on the east side of Broken Top.

Slab lava is pahoehoe that has broken into plates and slabs several inches thick and one to 5 feet in diameter. The plates and slabs are in a tumbled and chaotic mass (fig. 9). Slab lava is mostly seen where pahoehoe is beginning to change to aa, as in the Crystal Fissure flow. Flat, unbroken "roadways" of pahoehoe, that are probably over lava tubes, interrupt the jumbled slab lava in places.

Entrail pahoehoe is comprised of overlapping, twisted toes a foot or two in diameter. It occurs where viscous pahoehoe flows down a short, steep slope. It is seen on the sides of some pressure ridges and tumuli.

"Blue Dragon" pahoehoe is the term applied locally to lava that has glassy, iridescent blue or blue-white crust. The name was proposed by Russell (1902, p. 106). Unfortunately, the type flow recognized by Russell is not as extensive as he believed and is incorrectly located on the topographic map of the Monument. The Blue Dragon flow is discussed in another section. The blue crust is most common on thin flows and flow units of pahoehoe with bulbous toes. Many of the flows and flow units have issued from rootless vents. Most of the flows with a blue crust are very young, although a pitted and weathered "Blue Dragon" crust is present in a few places on some of the older flows. The Blue Dragon flow, the North Crater flow and many of the Lava Dome Complex flow(s?) are examples.

The cause of this iridescence is not known. It is most common on the top of the crust, but it is also found on the sides or undersurfaces of thin, broken pieces of the crust that are now turned upward, indicating that weathering or some external process acting soon after the eruption may cause the iridescence.

Pahoehoe Tubes

Tubes are common features of pahoehoe flows. The tubes in the Monument range from a few inches to about 50 feet in diameter. They range from a few feet to about half a mile in length, although some of the larger tubes were probably several miles long at the time eruption. Larger tubes near the vent subdivide and become smaller toward the flow margin. The toes of pahoehoe in the outer parts of flows are lava tubes. These small tubes are in places filled with lava. The discussion following will deal primarily with the large, hollow tubes that occur in the Monument.

The large tubes have been described individually by Stearns (1926?), and he gave a list of locations (Stearns 1928, p. 55). Further work has been done by Peter G. Sanchez, a geology student at the University of Utah, who has been a Seasonal Ranger and Naturalist at the Monument for the last several years. Sanchez has mapped some of the tubes and submitted reports on them to the Park Service. The writer is particularly indebted to Sanchez for telling him of many of his observations.

Most of the large tubes have been named and are located on the topographic map of the Monument as caves, tunnels, and natural bridges. One area, containing a number of large tubes that are not located on the map, lies just northwest of Grass Cone. Many large tubes may remain undiscovered, some because they are in remote areas and others because they have not been exposed by collapse depressions, which provide access to the known tubes.

Collapse depressions as much as forty feet in diameter pit the surfaces of pahoehoe flows over many of the lava tubes. These depressions are generally circular, although in some places a considerable length of the tube has collapsed (fig. 10). Some of the collapses occurred after the roof of the tube was completely solid. The floor of the depression may then be littered with fragments of the broken roof (fig. 11). Others collapsed while the roof was still plastic. The roof then sagged into an inverted continuous sheet, breaking only around the edge of the depression. Examples of each type may be seen beside the trail of Indian Tunnel. Natural bridges result from the near coalescence of two collapse depressions.

The detailed features of the large tubes indicate a complex evolution of the tubes and the flows that contain them. Numerous small flow units break through the roofs. These flow units can be seen in cross-section in the walls of the tubes. Tributary tubes diverge from the main one at various levels (fig. 12). Shorelines and terraces of solidified lava are on the lower walls of some of the tubes (fig. 13).

The terraces indicate the various level or levels of the waning flow within the tube as the supply of lava from the vent diminished near the end of an eruption. The floors are paved by the last flow unit to move through the tube. The walls are commonly glazed by gas action and may be covered with lava stalactites (fig. 14). Stalactites are discussed in a following section.

The temperature in the tubes during the summer is well below the surface temperature because of the insulating qualities of the basalt roof. A project is currently in progress to measure the temperature and relative humidity in the depths of one of the longer tubes, Arco Tunnel, throughout the year. Freezing temperatures exist in some of the tubes during the summer months.

Water, in places in the form of ice, is present in many of the tubes. The ice coats both the floors and the walls in some places. Stearns (1928, p.33-35) described and explained this phenomenon. The water comes largely from snow melting on the surface, augmented slightly by the occasional rains. The meltwater seeps through cracks in the roof and is trapped in the tube. The water may be frozen soon after it seeps into the tube and so veneer the walls as well as the floors with ice.

Thenardite, a secondary mineral, is present on the walls and in piles on the floors of some of the tubes. The mineral is a hydrated sodium sulphate. It is commonly in the form of

a powder, but in the depths of at least one tube, Arco Tunnel, the mineral is crystalline. The crystallinity is due to the low temperature and high relative humidity in this tube. Sanchez (oral communication) reports that crystals brought out of the cave invert to powder.

Lava Stalactites

Lava stalactites are present on the walls and roofs of most of the tubes. In some tubes they are abundant and in others rare. The stalactites range in length from a fraction of an inch to about $1\frac{1}{2}$ feet. The surfaces of the stalactites are glazed.

Two different modes of stalactite formation were described by Wentworth and Macdonald (1953, p. 55). Viscous lava may drip or droop from the under side of the roof soon after the roof has formed. Gases escaping from the pahoehoe river flowing in the tube may remelt portions of the solidified roof.

A third possible mechanism is suggested here. Some stalactites appear to have been stretched out like pulled taffy. Smooth grooves parallel the length of such stalactites. An extreme example of stretched stalactites was found in a small two feet-high, tube or gas blister in a spinose pahoehoe flow unit near the north boundary of the Monument (fig. 21). One broad, thin sheet was observed in this tube still connected both to the floor and the roof.

A small tube northwest of Broken Top has stalactites at two levels, the larger ones being at a higher level and exposed.

by the collapse (fig. 14). These stalactites are round in cross-section. Some have solidified trickles of lava running down their sides, and others have several bulbs of fused lava at their base. These features indicate remelting by gas, and the fact that they are at two levels indicate a possible origin for a stalactite-like feature seen in the cross-sections of the roofs of several collapsed tubes (fig. 15). The stalactite-like features occur in layers mostly attached at top and bottom. They are oval in cross-section and are often pinched in the center. Some are true stalactites. They all have glazed surfaces. It appears that this feature may be caused by the sagging of layers of plastic lava that were plastered on the roof of the tube by the lava river. This idea was suggested by Ray Wilcox of the U. S. Geological Survey (oral communication).

Stalagmites are rare or non-existent. Blocks of the roof that are covered with stalactites have fallen to the floor in many of the tubes, and these may be mistaken for stalagmites.

Pressure Ridges and Tumuli

Pressure ridges are updomed features, serpentine in plan view, that occur on many of the pahoehoe flows in the Monument. They commonly range from 8 to 15 feet in height and may be as long as a quarter of a mile. The bases of pressure ridges range in width from fifteen to thirty feet. Pressure ridges are extensively fractured. A wide, continuous, medial crack

is generally present on the top, extending parallel to the length of the ridge (fig. 16). Squeeze-ups of lava from the interior of the flow may occur in the medial crack. In places the squeeze-ups overflow and extend down the side of the pressure ridge. Squeeze-ups are discussed in a following section. Most pressure ridges observed in the Monument seem to be elongate parallel to the direction of the advance of the flow, most commonly along the outer margin of the flow. Some pressure ridges in other areas are reported to be oriented transversely to the direction of flow, but they are the exception, not the rule. Pressure ridges are formed on gentle slopes or flat areas.

Tumuli are updomed features similar to pressure ridges which are elliptical or round in plan view, their length being no more than a few times their width. They are not common features in the Monument. They average about eight feet in height. Round tumuli are more common in the Monument than elliptical tumuli. The fractures on these round tumuli generally radiate from the peak. The fractures may be filled with squeeze-ups. The tumuli in the Monument appear to be randomly distributed and have no general relation to the movement of the flow.

The origin of pressure ridges has not been satisfactorily determined. Wentworth and Macdonald (1953, p. 49) summarized the hypotheses. Pressure ridges have been attributed to rising gas, pressure of fluid lava, and differential collapse by draining away of the underlying lava. Nichols (1939a

and 1946) suggested horizontal pressure resulting from shortening the solid crust by the collapse or sagging of a domical raised portion of a flow adjacent to the pressure ridges and tumuli.

Tumuli and pressure ridges are not likely to result from rising gas because they are solid, not hollow. Large blisters may have been mistaken for tumuli by early workers. The pressure of flowing lava may form tumuli and pressure ridges that are oriented transverse to the flow. It is difficult to comprehend how the motion of the lava could exert a force at right angles to the movement of flow, sufficient to buckle the thick crust and form the pressure ridges that parallel the flow. Horizontal pressure resulting from crustal shortening may cause some of the pressure ridges. The creation of such horizontal pressure requires a broad dome of ponded lava adjacent to the ridge, and some of the ridges in the Monument occur where the flow is quite narrow, where the necessary dome could not have found room to occur.

Differential collapse due to draining away of fluid lava seems to be a valid explanation for some tumuli. Pressure ridges form where the lava is ponded, at least temporarily. The lava cools and congeals more quickly along the borders of the flow than in the centers. When the flow begins moving again, perhaps because of breakthroughs at the flow fronts, the center of the flow will move more rapidly than the edges because of its greater fluidity. The crust will sag as a

result of draining. The nearly solid lava along the margins will support the crust more strongly than the fluid lava, nearer the centers thus forming ridges. This process will sometimes result in an asymmetrical ridge with the steeper side at the outer margin provided that the center of the flow does not sag very much. This type of pressure ridge is present in the Buffalo Caves flow (fig. 17).

No single hypothesis adequately explains the formation of pressure ridges and tumuli. It may be that the solution to the problem is as yet undiscovered. It is likely that several of the explanations discussed above are valid, depending on the circumstances.

Squeeze-ups

Squeeze-ups are protrusions of lava that have been pushed up from the viscous underpart of a flow, either into or through cracks in the hardened crust. The squeezing is apparently owing to pressure exerted by the viscous lava under the crust. Squeeze-ups may be grooved as a result of squeezing of the plastic lava through the crust (fig. 18). Nichols (1939b) has described two types of squeeze-ups. Linear squeeze-ups are elongate and have rounded or wedge-shaped tops. Most of the linear squeeze-ups in the Monument have rounded tops. They occur in the medial cracks of pressure ridges. The Devil's Sewer Pipe is an example. Bulbous squeeze-ups are fluid and flow out onto the surface for a few feet. They may become flow units if they cover a large area. The pressure ridge

containing the Devil's Sewer Pipe also has some bulbous squeeze-ups that have flowed down the side of the ridge for a short distance (fig. 29).

Squeeze-outs

The term squeeze-outs is proposed here for the bulbs and tongues of "toothpaste" lava that commonly break through the margins of aa and block lava flows (figs. 20 and 21). Squeeze-outs are of pahoehoe, although they issue from the margins of aa flows where the flows have ponded or halted. Macdonald (1953, p. 183) and Stearns (1928, p. 21) stated that it is unknown for an aa flow to change to pahoehoe, yet Macdonald (1943, p. 251) stated, "Small flows of pahoehoe occasionally broke from the lower portions of aa", in describing part of the 1942 eruption of Mauna Loa. Macdonald (1953, p. 178) also described flow units of "toothpaste" lava issuing from aa flows. He stated that flow units of pahoehoe that appear to issue from aa are merely the result of pahoehoe flows burrowing under slightly older aa flows. This does not seem to be the case in the Monument. Squeeze-outs can be seen on the margin of the Crystal Fissure flow along the southeast side of Inferno Cone. Many squeeze-outs become flow units. The cause of this phenomenon is discussed in the section on aa.

Pahoehoe Flow Units

Flow units of pahoehoe may issue from either primary or rootless vents. The North Crater flow is made up of several "Blue Dragon" pahoehoe flow units that are from two to four

feet thick. Some of these are flow units that apparently issued in rapid succession from the vent in North Crater.

Squeeze-ups on pressure ridges and on roofs of lava tubes commonly become sufficiently extensive to be called flow units. The flow units thus formed are mostly "Blue Dragon" pahoehoe. They probably formed in a ponded flow because of a resurgence of lava from the vent. Many of the pressure ridges in the Monument are partially buried by flow units that issued from the medial cracks of the pressure ridges.

Lava may enter an old tube and break through to the surface. This may have happened at Great Owl Cavern, where the Blue Dragon flow originates.

Extensive "ponds" of pahoehoe occur in the centers of some aa flows. These "ponds" may have been caused by the squeezing-up of lava from a central pasty layer after the flow has halted. They may also have been caused by a new flow entering an old channel and breaking through to the surface. Several examples occur in the Big Craters Southwest flow.

Squeeze-outs of "toothpaste" lava from the terminal margins of aa and block lava flows are commonly extensive enough to be called flow units. The outer part of the unnamed flow 2 is made up of flow units of this type. The Serrate? block lava flow along the north boundary of the Monument has issued a number of flow units of spinose pahoehoe from its margin (fig. 22).

General

The aa flows are basalt. Aa flows have surfaces of jagged, spinose fragments (fig. 23). Wentworth and Macdonald (1953, p. 57-62) have emphasized that the fragments are only on the top and bottom of the flows and that almost all aa flows have a central massive layer that was a continuous pasty mass at the time of eruption. Lava rivers supplied the flow during the eruption. These rivers drained out in places at the close of the eruption, leaving open channels behind that braid the surface of some of the flows. Aa flows advance by means of bulging out of the central pasty layer which crusts over as clinker and breaks off in fragments that roll down the margin and are buried by the advancing flow. Wentworth and Macdonald (1953, p. 62-63) gave an excellent description of this process.

The aa flows in the Monument average 10 to 15 feet in thickness although some may be much thicker, particularly where the flow is partly block lava.

The flow surface may be called either aa clinker or, if the fragments are all fairly large, aa rubble. This is part of the classification of aa given by Jones (1943). The fragments are mostly black or grey, although some surfaces are oxidized red. Most of aa flows in the Monument contain many fragments of lava with pahoehoe characteristics mixed with

aa clinker and rubble and are actually transitional between aa and pahoehoe. They are called aa because the predominant nature of the flow surfaces and the apparent method of movement are more like aa than pahoehoe.

Vesicles are abundant in aa flows, but they are generally smaller than those in pahoehoe flows and have an irregular outline.

Aa Channels

The channels that braid the surfaces of some of the aa flows range from a few feet to about 20 feet in depth. The shallow channels are in the thin flows and the deep channels are in the thick flows that are partly made up of block lava. Channels are absent on some of the flows (fig. 23). It is believed that the lava river that fills the channel during the eruption has an upper, rapidly flowing portion and a lower, slowly moving, viscous portion (Wentworth and Macdonald, 1953, p. 63). In most places the upper portion drains away at the close of the eruption leaving a channel. In some flows the river has not drained completely, and a frozen river of spinose pahoehoe is left behind at only a slightly lower level than the rest of the flow. Where the channel has drained, fragments tumbled into it like talus so that most channels are v-shaped in cross-section.

Aa Flow Units

Flow units are not as quite as common in aa as they are in pahoehoe, but those that are present are generally thick.

A number of the aa flows are made up of two flow units, each flow unit averaging 6 to 8 feet in thickness.

The squeeze-outs of "toothpaste" lava that commonly become flow units should be mentioned here. Although they are pahoehoe in nature, they issue from aa flows. The ponds of pahoehoe that are present in the middle of some of the aa flows also probably came from the aa.

BLOCK LAVA

The block lava flows are andesitic basalt. They have a fragmental surface comprised of smooth angular blocks. The blocks are generally black. They range from a foot to about four feet in diameter. They are dense, nearly glassy in places, with irregular vesicles. The blocks are in places mixed with aa clinker, pumice, spatter, and ash. Fragments of old crater wall ranging from a few inches to about 100 yards in diameter are present in most parts of the flows. The large crater wall fragments, locally called monoliths, are discussed in a separate section. The flows may be up to 60 feet thick with channels 20 to 30 feet deep. The thick flows possibly have a central massive core, but individual flow units are commonly composed of discrete blocks and perhaps a central core of ash. The Serrate flow and Serrate? flows are examples.

Macdonald (1953, p. 182-183) has described block lava flows as being similar to aa and having a central massive phase, with blocks only on the surface. This appears to be

true of the west part of the Serrate? flow along the north boundary of the Monument. The flow there is at least 60 feet thick and is composed of block lava and aa mixed with transported crater wall fragments. Squeeze-outs and flow units of "toothpaste" lava have issued from the margin of the flow (fig. 21). These flow units originate from the bases of channels in the flow and are apparently the result of squeezing-out of lava from a central viscous mass.

The area around Surprise waterhole is quite distinct. Short, snakelike flow units, composed largely of discrete blocks, wind around mounds of ash and cinder (figs. 24 and 25). Many of the flow units seem to have cores of unconsolidated ash, although it is possible that ash from later eruptions has filled the interstices among the blocks. The flow units average 50 to 100 yards in length. Some are all block lava whereas others contain large amounts of aa, spatter, and pumice, mixed with numerous small crater wall fragments. Large monoliths are commonly present. Perret (1950, p. 95) described, "The block and ash flow, the latest, least gaseous, and feeblest expression of the nuee ardente....", observed during the eruption of Mount Pelee from 1929 to 1932. The flows described by Perret moved down the slope of the volcano under the force of gravity. The slope of the flow units near Surprise waterhole is gentle, and most of the flow units did not travel any great distance. Only one of the flow units could be traced to a definite source. The source was in a small crater on the side

of a cinder mound. The Surprise waterhole area appears to have been a fissure zone that rent asunder an old cinder cone. Fire fountains may have formed the cinder mounds and pumice while numerous vents erupted the many small flow units.

Some of the cinder mounds have large blocks, up to four feet in diameter, scattered around their bases. The blocks may have been erupted individually or may have spalled off of a growing spine. Both processes were described by Perret (1935 and 1950). Wentworth and Macdonald (1953, p. 63-64) described the spalling-off of angular debris from spines of solid lava pushing up from the surface of aa flows. A similar phenomenon occurred in a kipuka of block lava that is surrounded by the unnamed flow 2 (fig. 26).

MISCELLANEOUS FEATURES ASSOCIATED WITH THE FLOWS

KIPUKAS

A kipuka is an area of land that is completely surrounded by lava flows. The kipukas in the Monument range in size from a few square feet to several square miles. Some of the kipukas are parts of older flows that have been surrounded by younger flows. Innumerable kipukas of this type, both large and small, are present in most of the flows in the Monument. The surface of these kipukas is generally below, or at about the same level, as the surface of the surrounding flows. Cinder cones and fragments of cinder cones form kipukas that generally project well above the surface of the surrounding flows.

MONOLITHS

Monolith is the term applied locally to fragments of old, broken cinder cones that have been transported by lava flows. The term monolith is sometimes applied in geology to a spine of the type that was protruded from the surface of Mount Pelee during the eruption in 1929 to 1932. The term spine is in common use for such a feature; therefore, local usage is followed in this report, and the term monolith is used to describe transported cinder crags.

The fragments of cinder cones that have been transported by the flows range from a foot to about 200 yards in length. The large ones may project 60 to 70 feet above the surface of the flow and may be 60 to 70 yards wide.

Many of the large monoliths situated near the entrance of the Monument appear, at first glance, to have been carried by the North Crater pahoehoe flow (fig. 27). Closer inspection shows that this is not so, and that the monoliths are kipukas. The pahoehoe flows are not thick enough to have floated the monoliths. The pahoehoe flowed around the monoliths, leaving a moat-like depression between them and the flow (fig. 28). Stearns (1926?, p. 336) noted this. Some of the smaller fragments have been carried by the pahoehoe. Where this has happened the base of the fragments is coated with a sheath of pahoehoe (fig. 29).

The large monoliths all appear to have been transported by the thick block lava and aa flows. Fragments of block lava

and aa are present in many of the moats around the monoliths. Stearns (1926?, p. 337) thought that many of the monoliths had been carried as much as 3 or 4 miles from the vicinity of North Crater. Some monoliths are intact whereas others are tilted and broken. Large unbroken monoliths occur in several areas. These areas may have been the site of old cinder cones. The cones were disrupted and large fragments subsided and were displaced slightly by the lava flows. The broken monoliths in the Serrate and Serrate? flows may have come from a cone or cones located between these flows. If a cone did exist all traces of it are now gone except for two clusters of large unbroken monoliths in the area. The topography permits the inference that the Serrate and at least part of the Serrate? flows issued from this area.

The few large monoliths that form kipukas near North Crater appear to have been carried out from North Crater, perhaps by the unnamed flow 1. The cluster of large monoliths near Paisley Cone appears to be essentially in place. Stearns (1926? p. 338) recognized this.

FAULTS

Faulting in the Monument is mostly restricted to the Great Rift Zone. Faults generally trend either parallel or at right angles to the Great Rift Zone. The faulting is expressed in subsidence and tilting of parts of the cinder cones and flows.

The highway "graben" is located on the south side of the highway that passes through the Monument. A definite scarp extends southwest for about half a mile from the campground area. The scarp ranges from 15 to 40 feet in height and is nearly vertical in places. The southeast side is the down-thrown side and the scarp faces North Crater. The steep part of North Crater that faces the scarp may also have been faulted, but no direct evidence was found. The fault beheaded the Highway flow and must have formed soon after the eruption of the Highway flow. Small, thin sheets of pahoehoe from the Highway flow have oozed back down the scarp in a few places. The actual displacement cannot be measured because angular talus covers the base of the scarp and several later flows have filled the depressed area. The faulting may have been caused by subsidence of magma in the conduit that supplied the Highway flow.

Subsidence over conduits may have contributed to the disruption of some of the ancient cinder cones in the Monument. Subsidence may have disrupted the cinder cone that once occupied the site of the campgrounds and Park Service headquarters. The area just north of the Serrate flow, described in the section on block lava, may have been a large cinder cone that was first disrupted by eruption and later by subsidence.

Large slabs of lava flows, tilted at steep angles, drop out on some of the cinder cones. Such slabs occur on the south side of Silent Cone, the east and south sides of Broken Top and on the south side of a small unnamed cone a mile northeast

of the Information Center. These slabs may be as much as a quarter of a mile long. They range from a few feet to about 20 feet in thickness. Some extend as much as 60 to 70 feet up the side of a cone. All appear to have been tilted after they were completely solid. Stearns (1926?, p. 314) noted this. The bases of the slabs are covered by later flows. The slabs appear to have been tilted up by the forces causing the fissures that are so common in the Monument.

The slabs on Broken Top are possibly part of the Black flow. They were apparently faulted at the time of the eruption of the Buffalo Caves flow. Bombs and spatter are present in the fissure on the south side of Broken Top, and bright red spatter covers the top surface of a tilted slab at this locality. The Buffalo Caves flow has covered the base of the slabs on the south side of Broken Top. Two smaller flows have issued from the fissure on the southeast side of Broken Top and apparently augmented the Buffalo Caves flow, permitting the inference that all the faulting on Broken Top is contemporaneous.

The east side of Fissure Butte has subsided, apparently as a result of the fissures that split the cone and extend northwest for about a mile.

GROOVED LAVA

Grooved lava is a common feature in the Monument. Wentworth and Macdonald (1953, p. 57) stated, "Wherever moderately to highly viscous but still plastic lava, either aa or

pahoehoe, moves past an irregular edge or surface of more rigid lava or other rock, or is rubbed by such rigid rock moving past it, the grooves and striations formed in the plastic lava may becomed preserved." Grooves occur on the bottoms of squeeze-ups, on the undersides of slabs of pahoehoe crust that have been turned up, on squeeze-outs of "toothpaste" lava and on thin layers of flows of lava that are interbedded with cinder and ash in the cones. They may be partly covered with "shark-tooth projections" (Nichols, 1939b), which are small spines caused by the pulling away of the plastic lava from the over-riding or overridden surface.

Nichols and C. E. Stearns (1940) described grooved lava from two areas inside the south wall of the south crater of Big Craters. The grooves on the west side were located by the author. The grooves are on the surface of a slab of lava that projects from the inner wall. One piece of the slab is broken off (fig. 30). The slab dips gently into the crater wall and is overlain and underlain by ash, cinder and spatter. The grooves range from a fraction of an inch to several inches in width, with many of the fine grooves inside the broad ones. The grooves are parallel and extend approximately downdip toward the outside of the cone. Nichols and C.E. Stearns (1940, p. 29) ascribed the grooving to the movement of a single large fragment over plastic lava. It seems more likely that the numerous grooves were caused by the sliding of the overlying cinder layer down the outer slope of the cone. The numerous cinders

would all move in the same direction if the overlying layer slid as a unit.

LAVA TREE MOLDS

Hot lava surrounding a tree will chill and solidify, preserving the mold of the tree, while burning the tree itself. This happens in thin pahoehoe flows, at the edge of thick pahoehoe flows, or near vents where the base of the tree is covered with spatter.

Lava tree is the term applied locally to upright tree molds that project above flow surfaces. This happens either where the lower part of a flow drains away or the mold is formed by spatter. A large number of lava trees occur on Trench Mortar Flat in a thin, ash-covered pahoehoe flow, (fig. 31). These lava trees are from one to four feet high. Some contain molds of the branches as well as the trunk of the tree. Several of these molds are near the vent and are covered with spatter. The molds were apparently formed, at least in part, by the spatter. Stearns (1924, p. 370) originally thought these lava trees to be hornito-like structures formed around small vents and so named them "Lava mortars". He later (Stearns 1928, p. 29-31) recognized their true nature.

Tree mold is the term applied locally to molds that are vertical and entirely beneath the flow surface as well as those that are horizontal. The horizontal tree molds are present along the edges of some pahoehoe flows where the lava

apparently pushed the trees over. The insides of the horizontal molds have a checked pattern that simulates the impression of the tree bark. Stearns (1928, p. 31) ascribed this to the filling of shrinkage cracks in the wood by the plastic lava. The checks are present only on the horizontal molds and not on either the vertical molds or the lava trees.

No charcoal or wood has been found in any of the lava tree molds, indicating that the trees burned completely. The locations of most of the lava tree molds are shown on the topographic map of the Monument and Stearns (1928, p. 55) gave a list of locations.

XENOLITHS

Xenoliths are fragments of older rock that are foreign to the igneous rock in which they are found. The xenoliths in the Monument are fragments of banded, coarse-grained, metamorphic rock that were broken off of the walls of the magma chamber or the conduit and carried to the surface by the rising magma. The specimens examined under the microscope are discussed in the section on petrography.

The fragments range from about one inch to one foot in diameter. The white fragments with dark parallel bands contrast markedly with the black basalt (fig. 32). The observed contacts of the xenoliths with the basalt are sharp, except in one. One specimen found in a crater wall fragment had been broken and intruded by red basalt. Most of the xenoliths have been

found in the block lava flows, although they are also present in the pahoehoe and aa flows. This is probably because of the greater surface area and color contrast presented by the loose, black blocks.

WATERHOLES

Ice-cold water is present in many places in the Monument, even in the heat of summer. A number of waterholes are perennial. They may occur in the bottoms of fissures, in the central orifices of spatter cones and in the bottoms of deep channels in the block lava flows (fig. 33). One of the waterholes is under an overhanging ledge of rock in the northernmost crater on Sheep Trail Butte. Snow Cone, which is the northernmost of the chain of spatter cones extending southeast from Big Craters, sometime has snow in its central vent until well into the summer. The reasons for the occurrence of these perched waterholes are the same as those for the occurrence of water in lava tubes, described already. Stearns (1938, p. 33-35) has explained the occurrence of water in some detail. The basalt rock is an excellent insulator. Meltwater from the snow may be trapped on an impermeable layer of basalt. Some of the water may re-freeze with a drop in temperature. The ice and ice water in the interstices of the rock are protected from the heat by the insulating power of the basalt. Evaporation is slow owing to the temperature of the water. Some of the water is replenished by the ice melting. As a result a

drink of ice water may be had in remote areas of the Monument even on the hottest days. The author supplied himself with water for two days from Surprise waterhole, which is only about one foot deep and two feet across. The water level only dropped about an inch.

DESCRIPTION OF THE INDIVIDUAL FLOWS

GENERAL

The description that follows begins with the flows near the northwest end of the Monument and continues generally in order of outcrop down the Great Rift Zone.

It is important to note that the description of flows south of Big Cinder Butte, beginning with the Big Cinder Butte flows, is based on only a few days of field observation. The description of these flows is brief and is of doubtful reliability.

Stearns (1926?) has described the flows in a similar manner. He has also described the vents and cones in detail. The description here is mostly limited to the flows and the reader is referred to Stearns (1926?) for a description of the individual vents.

The abbreviations after the names of some of the flows refer to the designations of those flows on the geologic map. The numbers given to the unnamed flows carry no connotation of age.

SUNSET CONE FLOWS

Three flows have issued from Sunset Cone. All the flows are covered with a layer of ash and loess. A thick growth of sage mantles the flows, contrasting strikingly with the barrenness of most of the flows in the Monument. The flow tops are mostly oxidized red by weathering. Names are proposed for each flow based upon the direction of flow and the location of the vent.

Sunset Cone Northeast Flow (SuNE)

The Sunset Cone Northeast flow issued from a breached crater on the northeast side of Sunset Cone. The flow is pahoehoe and is made up of many pressure ridges and tumuli near the vent.

Sunset Cone West Flow (SuW)

The Sunset Cone West flow issued from a crater on the west side of Sunset Cone. The flow is almost completely buried by cinder and loess. A few pressure-ridge tops project through the cover.

Sunset Cone Northwest Flow (SuNW)

The Sunset Cone Northwest flow is made up mostly of aa that has issued from a parasitic cone on the northwest side of Sunset Cone. The flow is about 20 feet thick and overlies the Sunset Cone West flow.

GRASSY CONE FLOW

The Grassy Cone flow erupted, apparently simultaneously, from two craters on the north side of Grassy cone. Pahoehoe flows from the two vents merge imperceptibly on the north side of the cone. A cover of ash and loess supports a thick growth of sage, comparable to the growth on the Sunset Cone flows. The flow tops are red. A network of lava tubes, with tubes as much as 15 feet in diameter, extends out from the northwest crater. The contact of the Grassy Cone flow with the Sunset Cone West flow could not be located because of the cover.

NORTH CRATER? FLOWS

Only one of the several flows described below can definitely be stated to have issued from North Crater. All the flows seem to have erupted from the same general area. The most recent flow covers the older flows in the vent area, making it impossible to trace them to their source. Monoliths from kipukas in all but the Highway flow.

Highway Flow (North Crater Aa Flow)

The massive Highway flow lies mostly between Sunset Cone and Grassy Cone, on top of the flows from those cones. It has apparently advanced northward from North Crater. The flow is beheaded on the south by the Highway Fault. This is discussed in the section on faulting. The flow is a mixture of aa and large, tumbled segments of pahoehoe. The surface is braided with channels 10 to 20 feet deep. The flow margin on the north ranges from 10 to 50 feet in height. Flow units of aa

and pahoehoe, averaging 8 feet in thickness, enter the campground on the east margin of the flow.

Unnamed Flow 1 (Un1)

The unnamed flow 1 crops out in two separate areas. One part forms a small kipuka along the base of the Highway fault scarp. The other, larger part crops out about a mile northeast of Paisley Cone. The flow is mostly aa rubble and slab lava. Correlation between the two outcrops is made on the basis of their similar natures, including the presence of boulders of andesite? that have been carried by the flow (fig. 34). The andesite? flow is seen in place only in the cross-section of the "Highway fault scarp". The andesite? is readily distinguishable because it weathers light brown. The unnamed flow 1 apparently issued from the vicinity of North Crater and swept along the base of the scarp, either picking up talus or catching falling boulders on the flow top.

Flow units of pahoehoe, originating as squeeze-outs, occur along the north border of the flow. The flow units change to slab lava and mix with the overlying unnamed flow 2 that is described below. Kipukas of an old block lava flow, many containing monoliths, are present within the flow. The margin of this old block lava flow, which may be the Devil's Orchard flow, described in a following section, forms an escarpment as much as 30 feet high facing the highway.

Unnamed Flow 2 (Un2)

The unnamed flow 2 is flat pahoehoe that breaks into

slab lava and, in places, aa. The flow crops out in three areas. It forms a small kipuka in the crater of North Crater and another larger kipuka along the base of the Highway fault scarp. The third outcrop is much larger, extending generally northeast from the cluster of monoliths north of Paisley Cone. The outer part of the flow is made up of wide expanses of flat pahoehoe, broken in places by festoons, pressure ridges and slab lava.

It could not be determined whether this flow issued from North Crater. The kipuka of pahoehoe that crops out in the crater permits the inference that it does. However, the Big Craters Northwest flow is of the same nature as this flow, and it may be that the unnamed flow 1 is partly or entirely from Big Craters. This possibility is further discussed in the section on the Big Crater flows.

North Crater Flow

The most recent flow from North Crater is the only one that can be traced directly back to the vent. It is bulbous pahoehoe with a "Blue Dragon" crust that issued as at least 3 flow units. The basal flow unit is more massive than others and forms a number of pressure ridges in the east part of the flow. Numerous small flow units of "Blue Dragon" pahoehoe originating as squeeze-ups have issued from the pressure ridges. Circular collapse depressions, up to 50 feet across, pit the surface of the flow. Kipukas in the flow are formed by older flows and, near North Crater, by several monoliths.

SERRATE FLOW(S?)

Stearns (1926?, p. 339) has described the Serrate flow as a single flow issuing either from North Crater or the vicinity of the Highway fault. It is possible that the Serrate flow actually comprises 3 or 4 flows that may have issued from different vents. The flows are all block lava mixed with aa and ash. They have transported large monoliths. A detailed physical description and possible method of formation of these flows has been given in the sections on block lava and monoliths.

Devil's Orchard Flow

The area known as Devil's Orchard on the northeast side of Inferno Cone contains an old block lava flow and many large monoliths. The name Devil's Orchard is here proposed for the flow. The flow is blanketed with a thick layer of cinder and ash. Parts of the flow occur as kipukas in the North Crater? flows. This may be the flow whose north boundary forms the escarpment described in the section on the unnamed flow 1. Some of the large monoliths in this flow seem to be nearly in place and may mark the approximate site of the vent that issued this flow. The Devil's Orchard flow is at a lower elevation than the Serrate flow proper and appears to be overlain by that flow, as described in the following section.

Serrate Flow

The flow here called the Serrate flow occupies an area

a little less than a mile square, northwest of the Devil's Orchard flow. It is comprised mostly of block lava, some aa and ash. The channels in the flow appear to radiate out from near the northernmost part of the flow. The slope of the flow surface is generally south and southwest. The flow on the southwest is at a high level and appears to overlie the Devil's Orchard flow. These facts permit the inference that the flow issued from a vent somewhere near the north margin of the flow.

Serrate? Flows

Several flows may occur in the area along the north boundary of the Monument that has been described by Stearns (1926?, p. 339) as being part of the Serrate flow. Stearns (1926?, p. 383) described the area around Surprise waterhole as a dome of pahoehoe lava. There is, however, no pahoehoe lava in the vicinity of the waterhole. Block lava and ash cover the entire area (figs. 24 and 25). Surprise waterhole is in what may be either a channel or vent in the block lava. The peak at the waterhole is made by a large tilted monolith. The possible origin of the numerous short flows and flow units in this area was discussed in the section on block lava. Many vents may have contributed to the accumulation of block lava in this area.

A mile west of Surprise waterhole is another flow that is composed of block lava, aa and massive pahoehoe. Flow units of pahoehoe have issued from the edge of this flow along the

north boundary of the Mommment (fig. 22). The slope of the flow surface permits the inference that it advanced from the southwest. It may have come from an old cone that may also have been the vent that erupted the Serrate flow proper.

REGISTRATION WATERHOLE FLOW (Re)

The Registration Waterhole flow has been described as a lava prop or endogenous dome by Stearns (1926?, p. 343). It is actually a layer of agglutinate covering a thin aa flow that erupted from a vent on a section of Paisley Cone. Ray Wilcox of the U. S. Geological Survey suggests (oral communication) that the flow issued from a vent about thirty feet up on the cone. Several flow units of black, jagged aa extend southwest for about 100 yards from the vent. An underlying pahoehoe flow, that may have issued from the same vent, extends a quarter of a mile farther southwest. A perennial waterhole is in the flow just below the vent.

BIG CRATERS FLOWS

The elongate, multiple-cratered cinder cone known as Big Crater is situated on a fissure zone that has erupted several large flows, both of pahoehoe and aa, at different times.

Big Craters Northeast Flow (BINE)

An open fissure just north of Big Craters extruded a short pahoehoe flow to the east. A waterhole is located in the fissure. Many flow units are exposed in the walls of the

fissure and a little of the lava has been colored red and yellow by fumarolic activity. This flow may be approximately contemporaneous with the Big Craters Northwest flow, described below. It may also be slightly older. Stearns (1926?, p. 345) suggested that it is the oldest flow from Big Crater because of the degree of weathering and the thin coat of cinders on the surface.

Big Craters Northwest Flow

A vent on the northwest side of Big Craters was the source for an extensive pahoehoe and aa flow. Two flow units make up the flow. The flow changes from flat pahoehoe to slab lava and finally a mixture of aa and pahoehoe.

Part of the flow extends under the North Crater flow. It is possible that this is the same flow that was described previously as the unnamed flow 1. Part of the flow sweeps around Silent Cone and extends to the south, where it underlies the Big Craters Southwest flow. Kipukas in the flow near the west boundary of the Monument are formed by a north-trending chain of old cinder cone remnants.

Big Craters Southwest Flow

A large flow of aa mixed with small pahoehoe fragments extends southwest from the base of Big Craters for several miles. The main channels are covered with pahoehoe in places, notably near the source. Patches of pahoehoe crop out in places in the flow. These pahoehoe patches apparently issued from rootless vents where the flow ponded. Small monoliths

are present near the outer margin of the flow. The Big Craters Southwest flow overlies the Big Craters Northwest flow.

The east margin of the flow is indistinguishable from the margin of the Crystal Fissure flow described below, which is of the same type and was extruded at about the same time.

Unnamed Flow 3

Pahoehoe crops out south and west of the Big Craters Southwest flow. Much of this pahoehoe may be flow units that originated as squeeze-outs from the Big Craters Southwest flow. Insufficient time was available to study this area fully.

UNNAMED FLOWS 4

Undifferentiated block lava and aa flows occur along the west boundary of the Monument. These flows extend far to the west. They may be about the same age as the Serrate and Serrate? flows.

CRYSTAL FISSURE FLOW

Crystal Fissure is the name applied by Stearns (1926?, p. 369) to a fissure or fissure zone that extends southeast from the base of Big Craters. A chain of spatter cones marks the site of the fissure, and the fissure is named after one of them. For a detailed description of the spatter cones the reader is referred to Stearns (1926?, p. 369-371). Several open vents and small pit craters are present near the south

end of the chain of spatter cones. One of the vents contains a waterhole. Many thin flow units can be seen in the walls of the pit craters and vents. Some of the lava is colored red and yellow by fumarolic activity.

The flows issued from Crystal Fissure in a series of flow units that are pahoehoe near the source and change rapidly to a mixture of aa and pahoehoe. The change in the lava is apparently a result of flowing down the rather steep slopes around Crystal Fissure.

The southwest part of the Crystal Fissure flow is indistinguishable from the Big Craters Southwest flow. A small lava dome is present in this part of the flow. This dome is probably a rootless vent, resulting from ponding of the aa. Thin flow units of "Blue Dragon" pahoehoe have issued from the center of the dome. The dome is capped by two partial hornitos. A large tube, known as Moonshine Cave, is near the center.

Another rootless vent just northwest of Broken Top apparently resulted from the ponding of a lower flow unit of the Crystal Fissure flow. The lava from this vent is the pahoehoe and aa that extends between Broken Top and Big Cinder Butte. Part of the flow extends into an open fissure on the southeast side of Broken Top. The flow is overlain on the north by a later flow unit of aa from Crystal Fissure. On the south the flow overlies the Buffalo Caves flow and underlies the Big Cinder Butte Northeast flow.

The southeast part of the Crystal Fissure flow consists

mostly of two flow units of aa. The upper flow unit stops at the base of a steep slope near the fissure, and the lower one sweeps around the base of Inferno Cone. Squeeze-outs of "toothpaste lava" are common along the margin of the flow. At the end of the flow, these squeeze-outs overlie pahoehoe from the Lava Dome Complex. The Crystal Fissure flow overlies the Lava Cascades flow, described below. A thin flow unit of scoriaceous pahoehoe from Crystal Fissure overlies part of the aa in the area between Lava Cascades and Inferno Cone. Big Sink, an old collapsed lava dome, forms a kipuka in this pahoehoe.

LAVA CASCADES FLOW (La)

Lava Cascades is a large collapsed lava dome. The rim is encircled by a wide, essentially continuous crack that resulted from the collapse. Short thin pahoehoe flow units from the inside wall, flow down into the depression left by the collapse of the dome. Flow units of shelly pahoehoe that change to aa have issued from the east side of Lava Cascades. The flow is overlain to the east by the Indian Tunnel flow.

UNNAMED FLOW 5 (Un5)

A small collapsed dome just northeast of Broken Top has erupted a number of thin flow units of pahoehoe that change to aa a short distance from the vent. The vent is exposed in this dome and a waterhole occurs in it. The flow units overlie

the Lava Cascades flow.

LAVA DOME COMPLEX FLOW(S?)

A chain of gently sloping lava domes extends generally east from near Inferno Cone. Large lava tubes are present in some of the domes. The large tubes indicate a thick flow, but the dome appears to be made up mostly of thin flow units of pahoehoe flowing out in all directions from the high points. It may be that these domes are all rootless vents and that the pahoehoe flow units have broken through the roofs of tubes that were parts of a single large flow. This large flow may have originated in what appears to be a large collapsed dome located just south of Indian Tunnel. It is even possible that this dome was a rootless vent that was formed by the collapse of a secondary dome on a temporarily ponded flow which issued from the vicinity of Crystal Fissure or Lava Cascades. The name Lava Dome Complex is here used for the flow or flows that crop out in the entire area.

Indian Tunnel is one of the largest tubes in the Monument, being as much as fifty feet in diameter in places. Beyond this tube to the northeast is a series of large lava tubes of somewhat lesser size. The last tube in the series, Arco Tunnel, is about half a mile in length. A detailed map and report on this tube have been submitted to the Park Service by Sanchez, who has explored most of the tubes in this area. He suggested that the tubes are all part of a network in the same flow (oral

communication). The author agrees with this suggestion.

The flow units issuing from the lava domes are largely bulbous, "Blue Dragon" pahoehoe with a few flow units of flat, scoriaceous pahoehoe. The flow units overlap each other in many places making it difficult to determine the relative ages with any degree of certainty. They all were extruded at about the same time. The flow units overlies the Serrate, Serrate?, and Devil's Orchard flows and the unnamed flow 2 to the north, and the Lava Cascades and Black flows to the southwest.

Kipukas of aa are common. The aa may be a much older flow or an earlier flow unit of the Lava Dome Complex. Aa is present in the bottom of the collapsed dome south of Indian Tunnel. This aa may be an older flow unit.

BLACK FLOW

The Black flow is massive, black and grey-black pahoehoe that is completely surrounded by younger flows. No source could be determined for the flow. Large pressure ridges make up much of the flow. The flow was mapped as one of the younger flows by Stearns and others (1938, plate 13), but well defined contacts prove that it is overlain to the north by the Lava Dome Complex flow(s?) and to the south by both Buffalo Caves flow and the unnamed flow 7. The contacts on the south are discussed in the following section.

BROKEN TOP FLOWS

The flow described in this section erupted long after the formation of Broken Top. They have issued from fault fissures on the sides of the cone. These fissures are discussed in the section on faults.

Buffalo Caves Flow

Buffalo Caves are several lava tubes, about 20 feet in diameter, that extend from a fissure on the south side of Broken Top. The flow is a very flat, scoriaceous pahoehoe that forms low pressure ridges in several places (fig. 18). This flow is under the northeast flow from Big Cinder Butte and the Crystal Fissure flow. It overlies the Black flow to the north where the lava can be seen to flow into cracks in the Black flow and others. Stearns (1938, plate 13) thought that the Buffalo Caves flow was younger than the Black flow. He was apparently misled by the heavy growth of vegetation on the Buffalo Caves flow. The heavy growth of vegetation is due to the nature of the flow surface. Numerous shallow cracks in the Buffalo Caves flow permit the trapping of soil and water in more places than in the massive Black flow.

Unnamed Flow 6 (Un6)

Scoriaceous pahoehoe has erupted from a fault fissure on the east side of Broken Top. Most of the scoriaceous pahoehoe has flowed east. A patch of denser pahoehoe is contained within the fissure.

Unnamed Flow 7 (Un7)

A small dome of bulbous "Blue Dragon" pahoehoe flow units crops out east of Broken Top. The dome may be a rootless vent on the unnamed flow 6, described above. Both of these flows contain microlites of plagioclase that are significantly larger than the microlites in any of the other flows in the Monument.

(ca)? CAVE DOME FLOW (La)

The Cave Dome flow issues from a small lava dome that is located about three-quarters of a mile north of Great Owl Cavern. The dome contains an unnamed lava tube that is about twenty feet in diameter and one hundred feet in length. Three partial hornitos are present on the dome. Short thin pahoehoe flow units have issued from the dome. The flow units overlie the Crystal Fissure flow and the base of Big Cinder Butte. The origin of this dome is believed by the writer to be similar to that of the Blue Dragon flow, discussed in the following section.

BLUE DRAGON FLOW AND UNNAMED FLOW(S?) 8

The Blue Dragon flow was named by Russell (1902, p. 106). He believed this flow to have a much greater extent than it actually does. The flow may be shown incorrectly on the topographic map of the Monument. The Blue Dragon flow issued from a vent near Great Owl Cavern and flowed for at least a

mile to the south. It is made up mostly of a number of thin flow units of "Blue Dragon" pahoehoe. Tree molds are present in the flow along the edge of Big Cinder Butte.

Great Owl Cavern is a lava tube about fifty feet in diameter and four hundred feet in length. The tube is capped by a hornito about fifteen feet high. The size of the tube indicates that it was part of a very thick flow. The thick flow is the unnamed flow(s?) 8. It extends to the southwest beyond the margin of the Blue Dragon flow. There may be more than one flow present in this area.

The Blue Dragon flow is definitely younger than the unnamed flow(s?) 8 but the length of the interval separating them could not be determined. The Blue Dragon flow may have resulted from a later surge of lava from the vent during the same eruption that produced the unnamed flow(s?) 8. It may also have resulted from another eruption in the same area that issued lava, which then entered the already existing tube. It is also possible that the lava came from the Crystal Fissure flow. One of the main channels of the Crystal Fissure flow heads directly toward Great Owl Cavern. The lava may have entered an old tube and broken through to the surface. Wentworth and Macdonald (1953, p. 27) have described a similar phenomenon in Hawaii. The relation of the Cave flow, already discussed, to the Crystal Fissure flow is similar.

BIG CINDER BUTTE FLOWS

Big Cinder Butte is the largest cinder cone in the Monument. It was built during at least two different eruptions. The flows from this cone were not studied in detail.

Big Cinder Butte Northeast Flow (BcNE)

The most recent flow from Big Cinder Butte issued from a fissure that splits the northeast side of the cone. The flow is bulbous, "Blue Dragon" pahoehoe. It spreads over most of the area between Big Cinder Butte and Broken Top, overlying the Buffalo Caves and Crystal Fissure flows.

Derelict Flow

The Derelict flow is a short, black aa flow containing many monoliths. It extends southwest from Big Cinder Butte. A chain of crags and cinders borders the Derelict flow on the east.

Unnamed Flow 9

A large block lava flow crops out south of the chain of cinders and crags mentioned in the preceding section. Stearns (1926?, p. 354) suggested that this flow may have issued from a vent just beyond the cinder and crag chain.

TRENCH MORTAR FLAT FLOW (Tr)

A short thin pahoehoe flow has erupted from a fissure southeast of Big Cinder Butte. The fissure is bordered by spatter ramparts. The flow has a large number of lava trees on its surface. These lava trees are described in the section

on lava tree molds. The flow is almost completely covered with a layer of cinder and ash. It is overlain by the Buffalo Caves flow.

COYOTE BUTTE? FLOWS

At least one flow has issued from Coyote Butte. The author investigated the area only briefly.

Unnamed Flow 10 (Un10)

A short flow that is now completely buried by cinder has apparently issued from the north side of Coyote Butte. Stearns (1926?, p. 356-357) believed that this flow is part of the Sawtooth flow, discussed below. He stated that the cinder cover is caused by later eruptions that covered the flow near the Great Rift Zone. Field relations indicate that the unnamed flow 10 may be instead an older flow.

Sawtooth Flow

The Sawtooth flow is a thick block lava and aa flow that extends far beyond the south boundary of the Monument. The author only observed most of the flow from a distance, but the topography indicates that the Sawtooth flow issued from an area south of Coyote Butte. The relation between the Sawtooth flow and the unnamed flow 10 may be similar to the relation between the Serrate flow and the Devil's Orchard flow.

LITTLE PRAIRIE AA FLOW

Many fissures occur in the area between Crescent Butte and the Watchman. Most of the fissures are bordered by spatter, and a few of them contain waterholes. Many flow units of pahoehoe and aa were erupted from these fissures. A jagged black aa flow extends to the southeast from the south end of the fissure zone. Most of the aa has come from fissures that split both slopes of the Watchman. Stearns (1926?, p. 375) suggested that the black aa in the south part of the fissure zone may be slightly younger than the flow units to the north.

LITTLE PRAIRIE (FLOWS?)

Little Prairie is a cinder-covered kipuka located northeast of the Little Prairie Aa flow. The kipuka appears to be formed by an older flow or flows that may be comparable in age to the Sunset Cone and Grassy Cone flows.

MOSS CAVE FLOW (No)

The author did not visit Moss Cave. Stearns (1926?, p. 383) described the cave as a large lava tube in a flow in the south part of Little Prairie. It is not clear whether this flow is older or of the same age as the flow or flows comprising Little Prairie.

UNNAMED FLOW(S?) 11

Pahoehoe overlies Little Prairie on the northeast. The

area was not investigated or the flows differentiated and the contact with the Black flow was not determined.

ECHO CRATER? FLOW (Ec)

An old pahoehoe flow has apparently issued from the east side of Echo Crater. The flow is covered by cinder and is overlain by the Little Prairie Aa flow.

UNNAMED FLOW 12 (Un 12)

The unnamed flow 12 is a short pahoehoe flow that issued from a vent located on a south spur of Echo Crater. Field relations indicate that this vent was formed after Echo Crater.

THE SENTINEL FLOWS

At least two flows and possibly three have issued from The Sentinel at different times. Stearns (1926?, p. 360) noted that the north and south parts of The Sentinel appear to have formed during different periods of eruption.

The Sentinel West Flow (SeW)

The Sentinel West flow is an old pahoehoe flow that erupted from the west side of the Sentinel and flowed south. It is overlain by the Sawtooth flow.

The Sentinel South Flow (SeS)

The Sentinel South flow is a flow that has issued from the south side of The Sentinel as pahoehoe and changed to aa. Stearns (1926?, p. 361) noted that a large tube is near the

source of this flow. He also stated that this flow becomes aa about two miles from the vent. The topography and air photos indicate that this aa may be a separate flow. It is discussed in the following section.

Unnamed Flow 13

The aa and block lava flow that crops out south of The Sentinel may be either a separate flow or part of the Sawtooth flow. It is a thick black flow with many monoliths.

UNNAMED FLOW 14 (Un 14)

A pahoehoe flow in the crater on the south side of Split Butte may be from Split Butte or may be a flow that has entered the crater from elsewhere.

Fissure Butte Fissure Flow(s?)

A fissure zone that is over a mile in length split Fissure Butte sometime after Fissure Butte was built. At least one flow and possibly several have erupted from this fissure zone. An aa flow from the fissure extends between Fissure Butte and Split Butte.

Unnamed Flow(s?) 15

Old, red-topped pahoehoe crops out south of Fissure Butte. Several flows may be present in this area. They may have come from Fissure Butte or Sheep Trail Butte. The Bridge of the Moon is part of a lava tube that crops out in the west part of the area.

SHEEP TRAIL BUTTE FLOWS

Sheep Trail Butte is a cinder cone containing three interlocked craters, 1 or 2 of which are nested. The nesting of the craters may be due to subsidence as suggested by Stearns (1926?, p. 364). The cinders on this cone are large, dense, and black. There is almost no vegetation on most of the cone. This is because there is no ash or soil for the plants to take root in. Stearns (1926?, p. 363) believed that the lack of vegetation was due to overgrazing by animals making their way to the water-hole that is located in the northernmost crater. A few trails may be seen on the side of the cone.

Sheep Trail Butte North Flow (ShN)

Several spatter cones are situated on a saddle between Sheep Trail Butte and Fissure Butte. The flow from these cones is a short one that overlies the unnamed flow(s?) 16.

Sheep Trail Butte East Flow (ShE)

Pahoehoe has issued from the east side of Sheep Trail Butte. This pahoehoe is overlain by the Fissure Butte Fissure flow.

Sheep Trail Butte Southeast Flow

The south end of Sheep Trail Butte has erupted a lava flow that extends beyond the south boundary of the Monument. The flow is pahoehoe that changes to aa in about half a mile. The main channel is a wide collapsed tube that is bordered by spatter in many places. A number of smaller channels branch off of the main one.

VERMILION CHASM FLOW

Vermilion Chasm is a wide fissure bordered by high spatter ramparts. Several spatter cones and spatter mounds are on the floor of the fissure. Much of the spatter has been oxidized to a bright red color. Flow units have spread in all directions from this vent, but most extensively to the east because the vent is bordered on the west by the Sheep Trail Butte Southeast flow.

UNNAMED FLOW(S?) 16

A series of parallel fissures extends southeast from Vermilion Chasm beyond the Monument boundary. Most of the fissures are bordered by spatter ramparts. Some of the fissures contain ice-cold water. Numerous flow units extend in all directions from this fissure zone. A group of rootless vents in this flow trend east-west.

PETROGRAPHY

TERTIARY ROCKS

General

The Tertiary rocks described in the following sections are from the part of the Pioneer Mountains that lies in the north part of the Craters of the Moon National Monument. A study of these rocks was not considered vital to the project sponsored by the Park Service. As a result, only a few specimens were collected and examined. For a detailed petrography

of the rocks in the Pioneer Mountains the reader is referred to Anderson (1929).

Challis Volcanics

Quartz Latite Vitrophyre

Phenocrysts comprise about 30 percent of the quartz latite vitrophyre. The phenocrysts are mostly andesine and orthoclase, with some pseudomorphs of clinocllore after hornblende, and plates of biotite that have been extensively altered to penninite, rutile, calcite, and iron oxide. Inclusions of older lava are present. Small grains of orthoclase, quartz and an unidentified plagioclase are present in the ground-mass along with a large percentage of glass and cryptocrystalline material. The orthoclase is unusual, because sanidine is the expectable potassium feldspar. The glass and cryptocrystalline material exhibit flow structure. A few welded glass shards are present. Apatite, ilmenite, leucoxene, and a little hematite are accessories. The feldspars are extensively sericitized. Secondary stringers of chalcedony and calcite are in fractures in the rocks.

Basaltic Vitrophyre

Phenocrysts comprise about 30 percent of the basaltic vitrophyres. Some of the specimens are glomeroporphyritic with clusters of plagioclase phenocrysts. The phenocrysts are andesine-labradorite plagioclase, augite, and biotite plates, with a little olivine. Inclusions of basalt are common. Iron oxide is an accessory. The matrix is glass that exhibits

a pronounced flow structure or fluidal compaction around the mineral grains. A few welded glass shards are present.

E. F. Cook, Dean of the College of Mines, University of Idaho, observed (oral communication) that the flow or fluidal compaction structure appears to have been deformed plastically, and, in places, recrystallized. This rock may be a basaltic ignimbrite.

Miocene Intrusive

The Miocene intrusive rocks in the north part of the Monument all appear to be parts of the same stock. Anderson (1929a) has called this stock a granite, but noted that it ranges from granodioritic to granitic in composition. The specimens examined by the author ranged from granodioritic to quartz monzonitic in composition.

Phenocrysts are formed by calcic oligoclase, highly altered to clay, pseudomorphs of chlorite after hornblende, plates of biotite, in places altered to chlorite and epidote, and a few small phenocrysts of unaltered hornblende. The matrix is made up of anhedral quartz grains, subhedral grains of an unidentified plagioclase that is mostly altered to clay, and, in the felsic specimens, subhedral grains of orthoclase.

QUATERNARY FLOWS

Pahoehoe and Aa

The pahoehoe and aa flows are all olivine basalts. A typical specimen contains microlites of labradorite, small

grains of olivine, and euhedral grains of iron oxide in a matrix of glass that contains numerous small anhedral grains of iron oxide. Pyroxene is not in the groundmass, and was found in only one specimen as a phenocryst of pigeonite. The texture is generally hyalopilitic, and in places tends to be trachytic. Stearns (1926?, p. 291-292) reported a similar description made by Howell Williams.

The olivine is present mostly as either six-sided or rhomb-shaped sections in the groundmass. A few rounded microphenocrysts are present in some specimens. The olivine is colorless in plain light and is only very slightly altered. The alteration product is an almost indiscernable rim of what is probably serpentine that also penetrates fractures in the mineral. Greater resorption occurs with increasing depth in the flow. The optic orientation of the olivine is mostly negative and is indicative of an iron oxide content of greater than thirteen percent.

The labradorite microlites are normally lath-shaped. They increase in abundance with depth in the flow. Small anhedral grains of iron oxide cluster around many of the microlites. The abundance and size of these grains increase with depth in the flow.

Iron oxide occurs in two generations. The small anhedral grains described above occupy interstices among the feldspar microlites as well as cluster around them. Large cubes and octahedra of magnetite are present. These large grains

penetrate the other minerals.

Up to 70 percent of the basalt may be tachylite. This volcanic glass ranges from light brown to black in color. Lighter-colored glass is present near the tops of the pahoehoe flows. The index of refraction of the glass ranges from 1.585 to 1.595. This indicates a silica content of slightly less than 50% which is somewhat lower than the figure of 51.14% reported by Russell (1902, p. 87) from a chemical analysis of a specimen from an unknown flow in the Monument. The glass darkens and decreases in abundance with depth in the flow because of increasing abundance of iron oxide and greater crystallization of the component minerals. Incipient crystallization of the glass is reflected in the formation of crystallites that increase in size and abundance with depth.

Colorless spinel is an accessory in two specimens. The specimens are from the Sunset Cone flow and the Cave flow. Some of the spinel contains grains of magnetite that appear to be partly altered to green spinel (pleonaste?). In the specimen from the Sunset Cone flow the spinel may comprise nearly one percent of the rock.

Block Lava

The block lava flows are andesitic basalt. A typical specimen contains a few microphenocrysts of clinopyroxene and olivine. Xenocrysts(?) of sanidine that are partly absorbed are in a matrix consisting of microlites of andesine, grains of olivine and iron oxide, and dark glass. The microlites are

commonly needle-shaped. The texture is hyalopilitic. The index of refraction of the glass is about 1.55. This indicates a silica content of about 55%.

Andesite?

The andesite? flow is found in place only in the scarp of the Highway fault. Fresh surfaces are green with megascopic xenocrysts? of sanidine. Weathered surfaces are light brown. The flow top and bottom are moderately vesicular with an aa surface. A zone near the base of the flow exhibits curved platy jointing. The flow appears to be about twenty feet thick.

The texture of the andesite? is nearly holocrystalline. A few phenocrysts of clinopyroxene, partly resorbed, are present. Partly absorbed xenocrysts of sanidine with strong reaction rims are present. The matrix is sodic andesine microlites and colorless olivine, with a small amount of cryptocrystalline material. The microlites of andesine exhibit undulatory, parallel extinction. Iron oxide is an accessory. The cryptocrystalline material has an index of refraction of about 1.535. This indicates a silica content of 50% to 55%. Euhedral analcite is present as a secondary mineral in the interstices.

Xenoliths in the Quaternary Flows

Xenoliths of high-grade gneisses have been carried up from depth by the basaltic magma. Microscopic investigation indicates that they are pyroxene granulites of noritic composition. The specimens all have a similar mineral content

with the exception of one, which has a higher quartz content than the others. The author is particularly indebted to Rolland R. Reid, head of the Department of Geology at the University of Idaho, for his observations and suggestions in regard to these specimens.

The texture of the xenoliths is crystalloblastic. Porphyroblasts of unzoned calcic andesine and hypersthene are set in a matrix of xenoblastic grains of plagioclase, with subordinate quartz and orthoclase. The weak foliation is caused by parallel plates of biotite that have been almost completely altered to iron oxide. Relict grains of another pyroxene are present in places. The porphyroblasts of andesine have been sheared and the polysynthetic twin lamellae offset, but lamellae, as well as granulated quartz grains, do not exhibit undulatory extinction. Recrystallization after shearing is indicated. Andesine is in places myrmekitic. Plagioclase in the groundmass is mostly untwinned and is probably andesine. The quartz in the groundmass is partly in lenticular grains oriented parallel to the foliation.

SUGGESTIONS FOR FUTURE RESEARCH

The most pressing need for future research is the further mapping of the geology in the south part of the Monument. A considerable amount of field work needs to be done to unravel the sequence of events in this area. The further work done should then be correlated with the material in this

report and an attempt made to give a comprehensive geologic history of the Monument. Additional petrographic work should be done.

The extension of the Great Rift Zone to the southeast beyond the present boundaries of the Monument should be explored and an attempt made to add that area, with its spectacular spatter cones and ramparts, to the Monument. Exploration should be extended to cover the recent lava flows that extend beyond the Monument's boundaries and determine the relations of the recent flows to the flows of the Snake River Plain.

The lava tubes in the Monument should be mapped and described in detail. This work would aid considerably in the interpretation of many of the flows.

The area covered by the Devil's Orchard, Serrate, and Serrate? flows should be mapped in detail. An attempt should be made to recognize and separate the flows, and determine their origin.

Further mapping should be done in the Pioneer mountains to determine the boundaries of the various types of lava. Additional thin sections should be made and described.

Additional specimens of xenoliths should be prepared for petrographic analysis. A detailed study of as many of the xenoliths as possible should be made. This would be an important contribution to the understanding of the basement rock and the development of the Snake River Plain.

Finally, detailed petrographic study should be made of all specimens collected in the Monument, as well as specimens of the older Snake River Plain lavas. This should be done with a view to establishing the relation of the Monument to the petrographic province of the Snake River Plain.

- FIGURE 2. A spindle bomb on Big Cinder Butte that has been bent upon landing.
- FIGURE 3. Two spatter cones at the north end of the spatter cone chain on Crystal fissure. Big Craters is in the background.
- FIGURE 4. Spatter ramparts bordering a fissure southeast of Vermilion Chasm.
- FIGURE 5. Lava Cascades, a collapsed lava dome. The depression is about a quarter of a mile long. Broken Top is in the background.
- FIGURE 6. A small hornito in a kipuka in the Crystal fissure flow northeast of Broken Top. The hornito has issued from a crack in the flow.
- FIGURE 7. Festooned pahoehoe on a squeeze-up that has overflowed a pressure ridge.

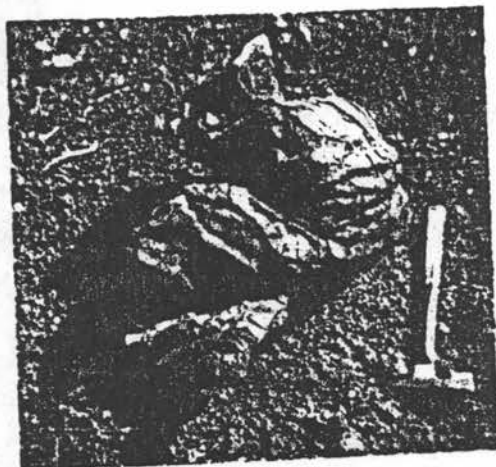


fig. 2

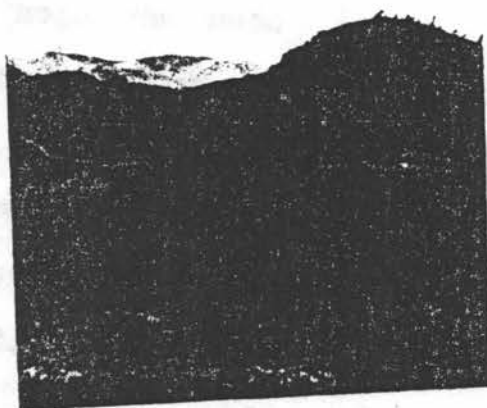


fig. 3

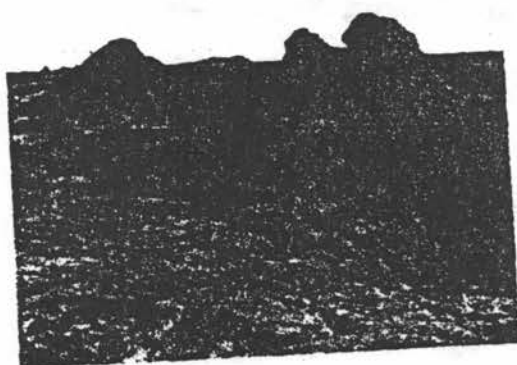


fig. 4



fig. 5

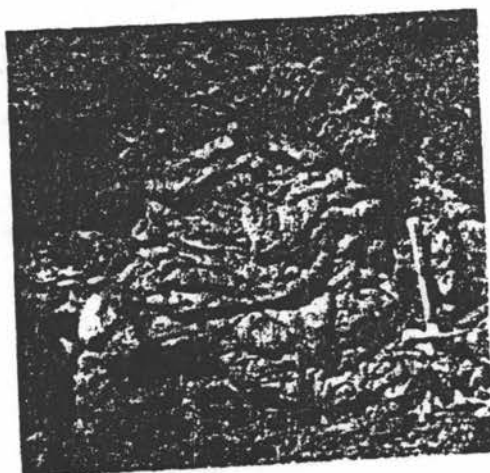


fig. 6

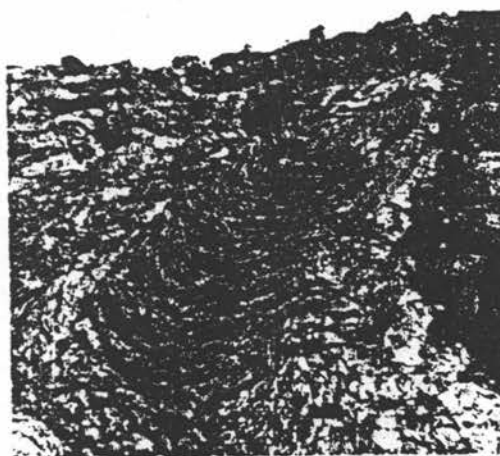


fig. 7

- FIGURE 8. Large festoons of pahoehoe.
- FIGURE 9. Pahoehoe breaking into slab lava near North Crater.
- FIGURE 10. A collapsed lava tube west of Surprise cave. The roof is virtually intact.
- FIGURE 11. A lava tube exposed by a collapse depression. Loose blocks cover the floor. A loop-shaped squeeze-up can be seen in the crack splitting the roof of the tube.
- FIGURE 12. Inside a lava tube in the Cave Dome. A small tributary tube branches from the main one. Some small stalactites are on the roof.
- FIGURE 13. A lava tube in the Grassy Cone flow showing terraces left by the subsiding lava river.

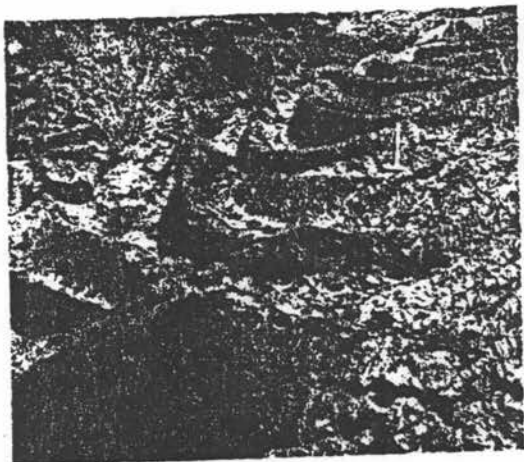


fig. 8

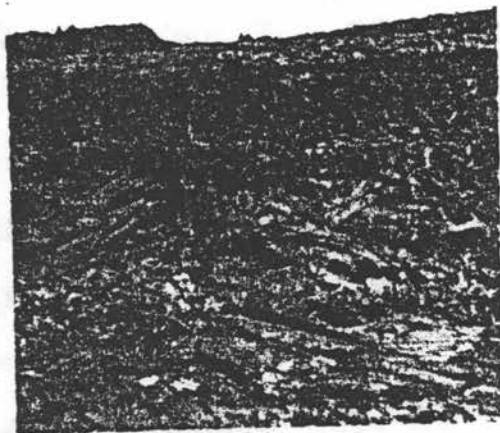


fig. 9

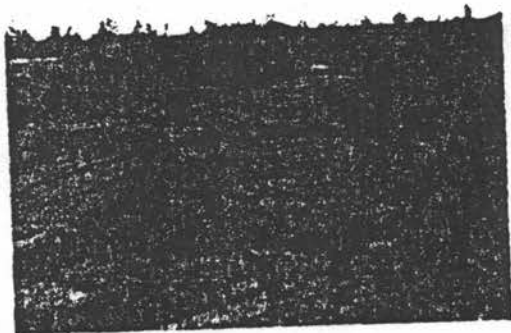


fig. 10



fig. 11

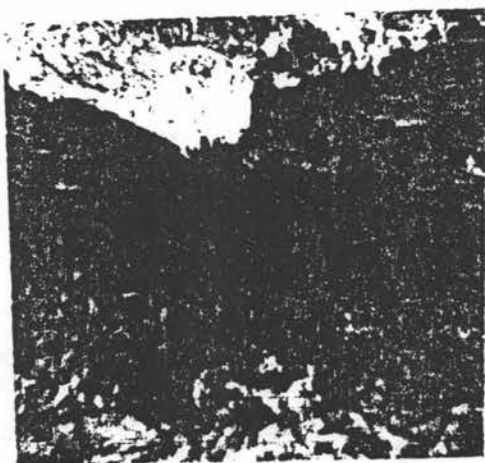


fig. 12



fig. 13

- FIGURE 14. Lava stalactites on the roof of a tube northwest of Broken Top. The large stalactites in the foreground are about a foot long and are at a higher level in the roof than the small stalactites in the background.
- FIGURE 15. Cross-section of the roof of the collapsed lava tube shown in Fig. 12. The small pillars may have been formed by the pulling apart of layers in the roof of the tube.
- FIGURE 16. Medial crack in a pressure ridge in the North Crater flow. North Crater is in the background.
- FIGURE 17. Pressure ridge on the margin of the Buffalo Caves flow. Part of Broken Top is on the right.
- FIGURE 18. Grooved squeeze-up near the base of the Highway fault scarp.
- FIGURE 19. Squeeze-up that has overflowed the pressure ridge containing the Devil's Sewer Pipe.

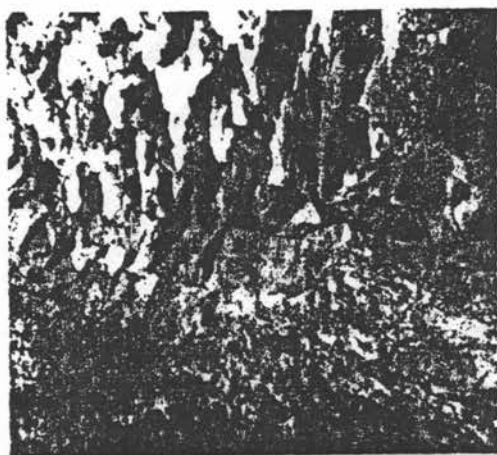


fig. 14



fig. 15

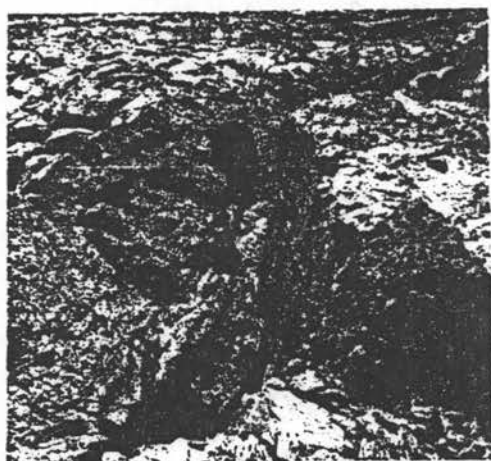


fig. 16

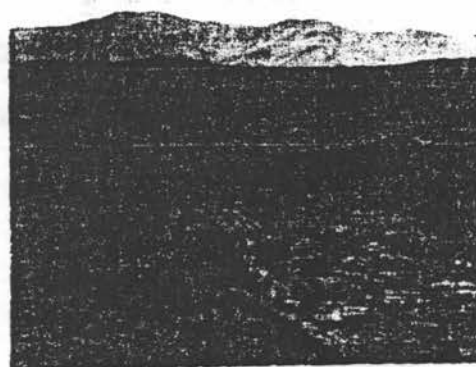


fig. 17



fig. 18



fig. 19

- FIGURE 20. Squeeze-out of pahoehoe from Serrate? flow near the north boundary of the Monument.
- FIGURE 21. Squeeze-out of "toothpaste lava" forming a small flow in front of a channel in the Serrate? flow near the north boundary of the Monument. The small tube or blister contains pulled sheets and stalactites of spinose pahoehoe.
- FIGURE 22. Flow units of pahoehoe issuing as a squeeze-out from the margin of the Serrate? flow near the north boundary of the Monument.
- FIGURE 23. Aa.
- FIGURE 24. Flow units of block lava or block and ash winding around mounds of cinder in the Surprise waterhole area.
- FIGURE 25. A flow unit of block lava along the margin of a mound of cinder in the Surprise waterhole area.



fig. 20



fig. 21



fig. 22



fig. 23



fig. 24

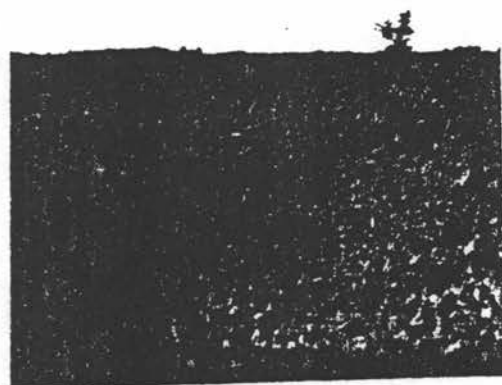


fig. 25

- FIGURE 26. A spine of block lava about twelve feet high in a kipuka in the unnamed flow 2. The spine has spalled off blocks that have fallen around its base.
- FIGURE 27. Monoliths forming kipukas in the North Crater Flow. These large cinder crags were transported by a block lava or aa flow that has been buried by the North Crater Flow. Grassy Cone is in the background.
- FIGURE 28. A monolith twenty feet high forming a kipuka in the unnamed flow 2, showing the moat formed by lava flowing around it. The flow that carried this monolith is now buried.
- FIGURE 29. A small fragment of a cinder cone that has been carried by a slab lava. Note the sheath of pahoehoe on the lower right side of the fragment. The fragment is about six feet in diameter.
- FIGURE 30. Grooved lava in the wall of the south crater of Big Craters. This slab has broken from the inside wall of the crater.
- FIGURE 31. A lava tree mold in the Trench Mortar Flat flow. The spatter rampart bordering the Trench Mortar Flat fissure is in the middleground.



fig. 26



fig. 27



fig. 28



fig. 29

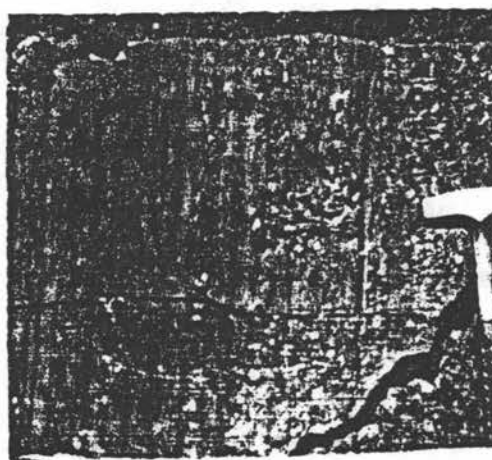


fig. 30



fig. 31

FIGURE 32. A xenolith in the Devil's Orchard flow. The white strip of paper is about three inches long.

FIGURE 33. Doves waterhole. A pool of ice water about six feet wide in the base of a deep channel in the unnamed flow 1. The flow is mostly block lava at this point.

FIGURE 34. Fragments of light brown andesite? that have been carried from the Highway fault scarp by the unnamed flow 1.

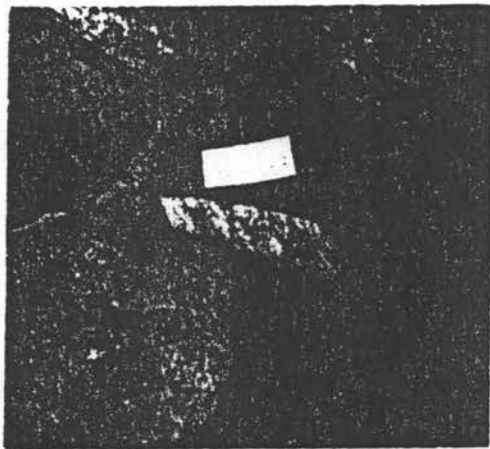


fig. 32



fig. 33



fig. 34

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