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TIME, VOLUME, AND WHOLE-ROCK COMPOSITION RELATIONS OF
HOLOCENE AND LATE PLEISTOCENE BASALT VOLCANISM
ALONG THE GREAT RIFT, IDAHO

by

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ABSTRACT

The Snake River Plain of southern Idaho is a region of late Cenozoic and Quaternary basalt volcanism. The plain contains many volcanic rift zones, the most spectacular is the Great Rift, an 85-km long, 2- to 8-km wide belt of cinder cones, shield volcanoes, eruptive and noneruptive fissures, and open cracks. Three Holocene and latest Pleistocene lava fields are aligned along the Great Rift. The Craters of the Moon lava field is composite; it consists of more than 40 lava flows erupted from more than 25 vents, covers an area of about 1600 km², and contains about 31 km³ of lava. Stratigraphic, radiocarbon, and paleomagnetic data indicate that lava flows of the Craters of the Moon lava field comprise at least 8 eruption periods that began about 15,000 years ago and ended about 2,000 years ago. Each eruption period was less than a thousand years duration and separated by repose intervals ranging from a few hundred to as much as about 2,000 years. The Kings Bowl and Wapi lava fields represent a small volume (0.01 km³) fissure eruption and a large volume (about 6 km³) shield eruption, respectively, that occurred simultaneously over a period of less than a few tens of years, about 2,250 yrs. ago.

Estimates of volume and age indicate that the eruption rate for nonevolved lava (<50% SiO₂) for the Craters of the Moon lava field has been about 1.6 km³/1,000 yrs for the last 15,000 years. The eruption rate of nonevolved plus evolved (>50% SiO₂) changed to about 2.8 km³/1000 years beginning about 7,000 years ago. Average whole-rock chemical analyses show that the lavas of the Craters of the Moon lava field evolved only slightly (44% SiO₂) from 15,000 to 7,000 years ago, increasing amounts of evolution (44% to 64% SiO₂) of lava compositions occurred after 7,000 years ago. The volume and composition data support heating of the crust and development of partial melts about 7,000 years ago, which subsequently led to more diverse lava compositions and increased eruption rates.

INTRODUCTION

The eastern Snake River Plain of southern Idaho (east of $114^{\circ}30'$ w. long.) is a region of about $25,000 \text{ km}^2$ that is a locus of young basalt volcanism. At least eight lava fields in that area are known or believed to be younger than twenty thousand years old: they include the Craters of the Moon, Kings Bowl, Wapi, Hells Half Acre, Cerro Grande, North Robbers, South Robbers, and Shoshone lava fields (fig. 1). These eight lava fields cover

Figure 1--near here

approximately 10 percent of the surface of the eastern Snake River Plain.

In this report, we describe radiocarbon, paleomagnetic, and lava volume data, and average whole-rock analysis data for three of these lava fields; Craters of the Moon, Wapi, and Kings Bowl. The three lava fields lie along the Great Rift, a volcanic rift zone that extends approximately 85 km from the southern Pioneer Mountains southeastward through the Craters of the Moon National Monument to Pillar Butte in the Wapi lava field, located about 30 km northwest of American Falls (fig. 1).

The Craters of the Moon lava field is the largest accumulation of dominantly Holocene basalt lava in the conterminous United States. It covers an area of 1600 km^2 and contains approximately 26 km^3 of lava. The Kings Bowl lava field covers about 3 km^2 , and the Wapi lava field is a shield volcano that covers an area of about 330 km^2 .

Regional setting

The Snake River Plain is an arcuate topographic depression in southern Idaho, 50 to 100 km wide, that extends from Payette on the west for about 250 km southeastward to Twin Falls and then for about 300 km northeastward to near Ashton (figure 2). The plain cuts across some of the most important geologic features of the western United States. It is bounded on the north by Mesozoic and early Tertiary granitic rocks of the Idaho batholith and by block faulted mountains that consist of folded Paleozoic and Mesozoic rocks uplifted along NW-trending normal faults during Basin-Range tectonism. Block-faulted mountains are also located on the southeast side of the plain, and Tertiary rhyolitic and basaltic rocks of the Owyhee Mountains bound the plain on the southwest. Late Tertiary and Quaternary rhyolitic and basaltic rocks of the Yellowstone Plateau are located at the northeast end of the plain (fig. 1).

The eastern Snake River Plain is a broad, flat, lava plain consisting, at the surface, of basalt lava flows and interbedded, thin, discontinuous, loess, eolian sand, and alluvial fan deposits that together have a total thickness of about 1-2 km near the area described in this report (Zohdy and Stanley, 1973; Stanley and others, 1977; Doherty and others, 1979). Lava flows of the eastern Snake River Plain were erupted from low volcanic vents that are generally aligned along volcanic rift zones that trend mainly at right angles to the long axis of the plain. Well-defined volcanic rift zones of the eastern Snake River Plain are as much as 10 km wide and 120 km long.

In the eastern Snake River Plain, the basalt volcanism represents the latest phase in a complex and poorly understood tectonic and volcanic history that also includes an earlier phase of rhyolitic volcanism. Available geological, geophysical, radiometric, and drilling data suggest that the rhyolitic rocks were erupted from a NE-trending belt of calderas that formed originally about 15 m.y. ago near Twin Falls and became progressively younger northeastward toward Yellowstone National Park. Models describing formation of the caldera system are discussed by Armstrong and others (1975), Eaton and others (1975), Christiansen and McKee (1978), and Mabey and others (1978).

The Great Rift and associated volcanic deposits

The Great Rift is a volcanic rift zone, a narrow belt of faults, graben, noneruptive fissures, eruptive fissures, spatter cones, spatter ramparts, cinder cones, lava cones, pit craters, and shield volcanoes whose vents are elongated over buried eruptive fissures (Wentworth and Macdonald, 1953; Kuntz, 1977a, 1977b, 1978). Cinder cones, eruptive fissures, associated lava flows and pyroclastic deposits, and noneruptive fissures constitute the 43 km-long, N. 35° W.-trending Craters of the Moon segment of the northern part of the Great Rift (fig. 2). The Great Rift emerges from beneath the southeastern

Figure 2--near here

limit of lava flows of the Craters of the Moon lava field as four sets of open cracks that trend N. 27° W. to N. 43° W. (fig. 2). The four sets of open cracks constitute an en echelon zone about 8 km wide from which no lava has erupted. The Kings Bowl lava field formed along an 11 km-long, N. 15° W.-trending segment of open cracks and eruptive fissures that is an extension of the westernmost set of cracks of the open-crack segment of the Great Rift (fig. 2). The lava flows of the Wapi lava field were erupted from at least 5 craters that form a vent complex at Pillar Butte. The elongated vents at Pillar Butte are aligned in a N. 20° W. direction and located about 7 km south of the Kings Bowl eruptive fissures which suggest that a segment of the Great Rift is buried beneath the Wapi lava field (fig. 2).

The lava flows, cinder cones, and the eruptive products (informal units in the upper part of the Snake River Group) of the three lava fields lie on older lava flows of the Snake River Group. The younger (Holocene and latest Pleistocene) lavas are dark-colored and dense in hand specimen, they have fresh, nearly unweathered, glassy (typically blue) crusts, and they are not covered by eolian sand or loess deposits. The older (Pleistocene) lavas are generally covered by a variable thickness of eolian sand or loess and exposed parts of the flows are light colored, less dense, weathered, and weakly to strongly oxidized.

Many volcanic rift zones in the eastern Snake River Plain appear to be extensions onto the plain of northwest-trending, range-front faults that bound block-fault mountains along the margins of the plain. In contrast, the Great Rift does not lie on an extension of a basin-range, range-front fault, but it may be an extension beneath the plain of a northwest-trending structure in older rocks that extends northwest beyond the margins of the plain. A magnetic high and gravity low centered in the area of Craters of the Moon National Monument probably reflects a deep seated intrusive body (Kuntz and others, 1980). The magnetic anomaly extends northwestward beyond the eastern Snake River Plain and is continuous with a northwest-trending magnetic high over a zone of Tertiary intrusive rocks for about 90 km northwest of the plain. The Great Rift and the zone of Tertiary intrusive bodies probably are the expression in the upper crust of a northwest-trending basement structure that extends across nearly the entire width of the ESRP and into the region to the northwest.

Lava flows

Most flows of the Craters of the Moon and Wapi lava fields consist of pahoehoe that forms flows that, in aggregate, have volumes that are typically more than 0.5 km^3 and less than 3 km^3 . The pahoehoe has hummocky, billowy, ropy, and wrinkled surfaces and toes and lobes that reflect the fluid nature of the lava and large-scale features such as pressure ridges, pressure plateaus and collapse depressions. The pahoehoe flows were typically fed through lava tubes and tube systems and rootless vents along lava tubes. The large-volume pahoehoe flows formed from the eruption of large volumes of degassed lava (Swanson, 1973) from point-source vents such as cinder cones and lava cones aligned along eruptive fissures, and also from short ($< 1 \text{ km}$) segments of eruptive fissures.

Some flows in both the Craters of the Moon and Wapi lava fields are of a'a lava that have steep flow fronts as high as 30 m and rough, jagged, clinkery surfaces. Large areas of the surface of a'a flows consist of irregular blocks of broken lava, some of which are broken slabs of shelly pahoehoe. Many surfaces of a'a flows in the Craters of the Moon lava field are littered with huge blocks and monoliths of well-bedded cinders and spatter. Evidently the eruption of some a'a-forming lava was so violent that it caused the collapse of the walls of source vent cinder cones and the monoliths were rafted away. A few flows consist of block lava that is characterized by irregular blocks of dense, glassy lava with smooth surfaces.

We use the term "fissure-flow" to describe flows of small volume, typically $<0.5 \text{ km}^3$, that consist mainly of shelly pahoehoe (Swanson, 1973). The fissure flows were formed by the outwelling of lava streams along segments of eruptive fissures as long as 5 km. Fissure flows constitute most of the Kings Bowl lava field and small volumes of lava that are located adjacent to eruptive fissures in the Craters of the Moon lava field.

Eruptive fissures

Eruptive fissures are strikingly displayed in the Craters of the Moon National Monument in the Trench Mortar Flat area between Big Cinder Butte and The Watchman cinder cones and along the Kings Bowl segment of the Great Rift (fig. 2). "Curtain of fire"-type eruptions took place on segments of the fissures as long as several kilometers. The fountains built low walls of agglutinated spatter along several kilometers of the fissures and produced spatter ramparts. Gas-charged lava flowed away from the fissures to form thin, shelly pahoehoe flows. After the curtain of fire phase of a fissure eruption, lava typically erupted from one or two places along the fissures and formed low spatter and cinder cones.

Cinder cones

Cinder cones are found widely scattered throughout the eastern Snake River Plain but they are best developed in size, shape, and number along the Great Rift, mainly in Craters of the Moon National Monument. Here, more than 25 major cones occur in a zone about 28 km long and as much as 2.5 km wide (fig. 2). The cinder cones are composed of cone-like accumulations of agglutinated and non-agglutinated tephra, and thin lava flows. In the Monument area, prevailing winds from the west and southwest caused greater downwind accumulation of tephra on the east or northeast sides of many cinder cones (fig. 2). Composite cinder cones formed by overlapping accumulation of ejecta from several contemporaneous or nearly contemporaneous lava fountains aligned along the eruptive fissure. Many cinder cones are breached on the northwest and (or) southeast flanks at localities where lava flows erupted along a feeder fissure and eroded previously accumulated cone walls or where ejecta was removed by a lava stream that flowed from the feeder fissure during formation of the cones.

Lava cones and small shield volcanoes occur at a few localities in the southern part of the Craters of the Moon lava field. The Wapi lava field is a shield volcano formed by the accumulation of a'a and tube-fed pahoehoe flows.

METHODS OF STUDY

This report summarizes various field and laboratory studies that we have carried out over the last ten years. We describe our methods in some detail because both the success and limitations of the methods bear directly on our conclusions.

Field and remote sensing methods

Reports by Russell (1902), Stearns (1928), Murtaugh (1961), and Prinz (1970) outlined the basic geologic framework of the Craters of the Moon lava field. Lefebvre (1975) identified four major groups of lava flows or eruptive pulses in the lava field by analysis of Landsat images. Champion and Greeley (1977) conducted preliminary studies on the paleomagnetic properties of the Craters of the Moon lava flows and found that paleomagnetic methods could be used both as a relative dating method for individual flows and as a correlation technique for lava flows that are separated from one another but believed to be coeval on the bases of field characteristics and stratigraphic relations. Our combined field studies in the summers of 1978 and 1979 made use of Lefebvre's gross stratigraphic relations for major eruptive units, Champion's paleomagnetic data, and preliminary 1:24,000-scale photogeologic maps of the Craters of the Moon lava. We mapped the entire lava field and collected samples for radiocarbon, paleomagnetic, and petrographic studies and for chemical analyses. A map (1:125,000) and descriptions of the Craters of the Moon, Kings Bowl, and Wapi lava fields were published by Kuntz and others (1980, 1981). A map of the Kings Bowl lava field (1:48,000) was published by Covington (1977).

Radiocarbon studies

Prinz (1970) reported an age of $2,130 \pm 60$ yrs. b.p. for charcoal from beneath the Kings Bowl lava field and Valastro and others (1972) reported ages of about 2,100 yrs b.p. for charcoal from tree molds from some of the youngest flows in the Craters of the Moon lava field. We have determined thirtyfive additional radiocarbon ages for flows in the Craters of the Moon lava field from organic soil and charcoal samples. The soil and some of the charcoal samples were obtained by excavating beneath lava flows with a backhoe. We selected excavation sites at locations along the margins of the lava field where tongues and lobes of lava flowed across relatively thick accumulations of loess and eolian sand. A black organic soil layer, about 1 to 10 cm thick, typically occurs beneath the flows at such locations and extends to within 0.2 to 1 m of the edges of the flows. The organic soil consists of fine-grained particles of charcoal and films of dark organic material on sand and silt particles. The soil samples also generally contain modern roots owing to the fact that the organic soil layer beneath the lava flows retains moisture in the arid climate of the eastern Snake River Plain. We believe that the layer of organic material immediately beneath the lava flows was produced by burning sagebrush and grass when the soil was overridden by the lava flows and by addition of organic material from roots that have grown and decayed in the soils after burial by lava flows. The roots are not charred and apparently are younger than charcoal in the charred soil matrix of the same samples. Soils developed in loess that is not covered by lava flows do not possess the dark organic soil layer.

Where present, charcoal was used for the radiocarbon dating. For most samples however, charcoal was not present and organic soil was dated. Since the organic carbon content of these soils is typically low (less than 2 percent), the carbon in the soils to be dated was first concentrated by a method of disaggregation and clay deflocculation with sodium pyrophosphate, followed by wet sieving (Stuckenrath and others, 1979; Goh and Molloy, 1978). The organic carbon in the less-than-125 um size fraction was leached with dilute HCl acid to remove traces of carbonate carbon. The preliminary radiocarbon ages on the organic carbon samples treated by the disaggregation-deflocculation-acid treatment, labelled "S" in Table 1, were

Table 1--near here

significantly younger than expected when compared to the radiocarbon age of charcoal from the same sampling locality. For example, a nine thousand year difference exists in the age of the organic soil and of charcoal for the Sunset flow (Table 1). Visual examination revealed fine hair-like roots in the organic carbon samples that had been prepared by the disaggregation-deflocculation-acid method.

Removal of the uncharred, contaminating roots was attempted by chemical digestion because the charred carbon is refractory and should be more resistant to chemical degradation. The organic soil samples were boiled in a 15 percent sodium hydroxide solution for 1 hour, then allowed to stand in this solution overnight at 70^o C. The resulting dark brown solution was decanted, discarded, and the procedure was repeated several times until the solution became clear. The samples were then leached with dilute HCl acid, filtered, washed, and dried. The alkali-acid pretreatment removed most of the organic carbon and all of the visible roots. The resulting radiocarbon ages for the organic soil and charcoal samples treated by the alkali-acid method (labelled "s-a" and "c-a" in Table 1) were significantly older and more consistent with the correlations based on field and paleomagnetic data, and with ages determined previously by radiocarbon analyses of charcoal (Prinz, 1970; Valastro and others, 1972).

Radiocarbon measurements were made by the standard acetylene gas counting method at the U. S. Geological Survey radiocarbon laboratory, Reston, VA. Sample activities were not corrected for isotope fractionation by a ¹³C measurement. The ages were calculated relative to the U. S. National Bureau of Standards oxalic acid standard activity (Stuiver and Polach, 1977).

There are principally two factors that limit the accuracy of the ages listed in Table 1. First, it is not certain that all of the younger carbon contaminants were removed by the alkali-acid pretreatment process. These dates should therefore be considered as minimum ages for the sampled horizons and the flows that overlie them. Second, these soils may contain a small component of refractory humus, coal, or graphite of much older age, presumably derived from eolian dust. This refractory carbon would tend to be concentrated as a result of the pretreatment process. Because few if any of the ages were older than expected, contamination by this old refractory carbon is probably minimal. It is possible, however, that both types of contaminating carbon persisted in the dated samples, the effect of one perhaps cancelling the effect of the other. We conclude that the ages on the charred soils are of variable accuracy, and probably represent minimum ages for their respective flows.

Paleomagnetic studies

Paleomagnetic measurements have been used to correlate lava flows, to obtain rough age designations for individual flows and groups of flows, and to decipher the volcanic history of the lava fields along the Great Rift. Each lava flow preserved a record of the local geomagnetic field at the time of eruption and cooling. Paleomagnetic field directions from the principal lava flows have been obtained and are listed in Table 2. With the knowledge that

Table 2--near here

the geomagnetic field changes due to secular variation at a geologically rapid rate (4° /century), comparisons of paleomagnetic directions have permitted assignment of lava flows to groups of similar paleomagnetic direction. Conversely, dissimilar paleomagnetic directions are strong evidence that two lava flows do not belong to the same group.

The paleomagnetic study proved to be extremely helpful in unravelling some difficult stratigraphic problems for the Craters of the Moon lava field. For example, we initially thought that thick a'a flows in the southern part of the Craters of the Moon National Monument all belonged to the same eruption period and that all were erupted from a source vent at or near Big Cinder Butte. On the basis of paleomagnetic data, it was possible to split the a'a flows into two basic groups with different inclination values, and to determine that at least two (Big Craters and Silent Cone cinder cones) source vents existed for the a'a flows. Petrochemical data and radiocarbon ages have led us to split one of the two initial a'a groups into two additional groups. Similarly, we correlate the Sunset and Carey tongues of lava that flow northeast and southwest respectively from the northern part of the Great Rift because they have identical paleomagnetic field directions. Without the paleomagnetic data, we might have assumed that the Carey and Sunset flows represented separate eruptions from separate source vents.

Estimates of areas and volumes of lava

The areas of lava flows of the Craters of the Moon, Kings Bowl, and Wapi lava fields were determined by polar planimeter from 1:125,000 scale geologic maps. Errors in estimating areas of individual flows of eruption periods older than the youngest period come from our inability to make accurate estimates of the areas of older flows now covered by younger flows. We extrapolated buried contacts back to known or reasonably inferred source vents and determined the inferred areas by polar plainimeter from 1:125,000 scale maps. The volume of each individual lava flow was determined by multiplying its area by an average thickness for each type of lava flow. Our field data and topographic profiles indicate that average thicknesses for types of lava flows are: shelly pahoehoe flows from fissure eruptions (5 m), tube-fed pahoehoe flows (10 m), a'a flows (15 m), and block-a'a flows (20 m). Estimates of the area and volume of individual lava flows and the volume of all flows in an eruption period (table 3) may be in error by as much as 50

Table 3--near here

percent, particularly for older flows and eruption periods. We feel however that overestimates and underestimates of areas and volumes of flows probably cancel each other out in determining the volume of flows for an eruption period.

CRATERS OF THE MOON LAVA FIELD

Volcanic history

We have combined individual lava flows and groups of flows that are believed to have similar ages, based on field, radiometric, and paleomagnetic data, into what we term eruption periods. Eight eruption periods are recognized in the Craters of the Moon lava field (Table 4). Figure 3

Table 4 and Figure 3--near here

illustrates the age and duration of each eruption period and shows the approximate length of time between eruption periods. Because we obtained radiocarbon ages from only some of the flows in each eruption period and because our radiocarbon studies have yielded only minimum ages, the age of the beginning, end, and duration of each eruption period is uncertain. The intervals between eruption periods may have been times of volcanic quiescence or reduced volcanic activity and the time within an eruption period may have been a period of nearly constant or sporadic eruptive activity; we cannot be more specific because many lava flows have not been dated and they cannot be dated in the foreseeable future. Table 4 also lists informal names that we have used for major flows in each eruption period. Figure 4 shows the

Figure 4--near here

sequential development of the Craters of the Moon, Kings Bowl, and Wapi lava fields during the eight eruption periods.

The oldest lava flows that we assign to eruption period H of the Craters of the Moon lava field flowed away from the general location of the Great Rift. This relationship suggests that the Great Rift was a locus of source vents for even earlier flows of the lava field and that these flows are covered by younger flows. Thus we recognize that our studies may treat only a later part of the history of the Craters of the Moon lava field rather than its complete history.

Eruption period H

The earliest recognized eruption period (H) in the formation of the Craters of the Moon lava field produced pahoehoe lava flows about 15,000 yrs. ago. These flows are now located near the margins of the lava field (Kimama, Brown, Bear Den Lake, Baseline flows) and as exposures in kipukas along the Great Rift south of Crescent Butte (Little Prairie, Lost Kipuka flows) (fig. 4H). The distribution and flow directions in the limited exposures of these flows suggest a source vent on the Great Rift, possibly at Echo Crater or Crescent Butte or both.

The flows of eruption period H have surfaces that are more weathered than flows of younger eruption periods of the lava field, but they have little or no cover of eolian sand or loess, thus we distinguish the flows of interval H from older, loess- and sand-covered, more deeply weathered flows that are not part of the Craters of the Moon lava field. Because the flows of eruption period H occur as widely scattered exposures that not have few mutual contacts and because we have few radiocarbon ages for flows of the group, the stratigraphic order of the flows in Table 4 and their absolute age are largely speculative. The age of 15,100 yrs. b.p. appears appropriate for the Kimama flow (Table 1) based on stratigraphic and other radiocarbon evidence, but we can not be more specific about the beginning or the end of eruption period H.

Eruption period G

About 12,900 years ago, eruptions took place from at least 4 vents along an extension of the Great Rift in the southern Pioneer Mountains, about 2 to 5 km northwest of the northern boundary of Craters of the Moon National Monument near the headwaters of Lava Creek (figs. 2 and 4G). The a'a flows from the Lava Creek vents traveled as much as 19 km to the east onto the Snake River Plain. The Lava Creek flows are some of the least evolved (about 44% SiO₂, Table 5) lavas of any erupted along the Great Rift, thus they probably acquired their a'a character because they descended steep slopes from their source vents to the plain. The complex Sunset Cone cinder cone and its associated flows were also formed during eruption period G. The Sunset flows moved as much as 20 km to the northeast and partly covered the Lava Creek flows. Voluminous pahoehoe moved as much as 53 km to the southwest and formed the Carey flows (fig. 4G). We correlate the Sunset and Carey flows with the same source vent at Sunset Cone based on similar paleomagnetic directions for the two flows, thus the radiocarbon age of 12,010 ± 150 yrs. b.p. for charcoal from the Sunset flows also applies to the Carey flows. The radiocarbon ages of the Carey flows (Table 1) probably reflect contamination by modern carbon inasmuch as they were not treated by the alkali-acid method for the removal of modern roots.

Eruption period F

Pahoehoe flows (Pronghorn, Bottleneck Lake) along the southwestern margin of the Craters of the Moon field (fig. 4F) were erupted about 10,000 to 11,000 years ago. The distribution and flow directions of the Pronghorn and Bottleneck Lake flows suggest a source vent on the Great Rift near the present site of Sheep Trail Butte (figs. 2 and 4F). Pahoehoe lava flows along the eastern margin of the lava field (Heifer Reservoir flows, fig. 4F) have a radiocarbon age of 10,600 yrs. b.p. (Table 1), thus we assign these flows to eruption period F.

Eruption period E

We believe that eruption period E began about 7,800 yrs. b.p. with the eruption of the Lava Point a'a flows. The Lava Point flows are contiguous with other a'a flows located near the southern boundary of Craters of the Moon National Monument. However, we assign the the Lava Point flows to eruption period E based on the radiocarbon age (Table 1). The proximal parts of the Lava Point flows are covered by younger flows but flow directions of the distal parts and paleomagnetic data suggest a source vent on the Great Rift northwest of Echo Crater (figs. 2 and 4E).

Grassy Cone, a complex cinder cone on the Great Rift in the northern part of the Monument (figs. 2 and 4E), formed after the eruption of the Lava Point a'a flows. Pahoehoe flows from Grassy Cone travelled as much as 52 km to the south and formed the Grassy Cone and Laidlaw Lake flows which, together, created the long, narrow, composite flow along the western and southwestern margins of the lava field (fig. 4E). The stratigraphic and radiocarbon data indicate that the Laidlaw Lake flows are older than the Grassy Cone flows, that both flows formed after the Lava Creek flows, and that both flows were erupted within a short period of time about 7,400 yrs. b.p. (Table 1).

Eruption period D

Eruption period D is characterized by bulbous, monolith-strewn a'a flows that are located south and southwest of Craters of the Moon National Monument (fig. 4D). All of the a'a flows are covered by younger flows in their proximal parts, but flow directions in their distal parts and paleomagnetic data suggest that all or most of them were probably erupted from Silent Cone. Slumped walls and rafted monoliths (cone wall remnants) indicate that the eruptions of the Silent Cone, Carey Kipuka, Little Park and Little Laidlaw Park a'a-forming lavas destroyed much of the north side of Silent Cone.

Eruption period C

Eruptions from fissures and cinder cones along a 9-km long segment of the Great Rift between Sheep Trail Butte and Echo Crater (fig. 2) produced the Sentinel, Fissure Butte, Sheep Trail, and South Echo lava flows (fig. 4C). These flows consist of pahoehoe near their source vents but several change to a'a several miles away from the vent. Paleomagnetic evidence indicates that eruption of the Sentinel flows preceded the other flows by several decades or perhaps by as much as a century. Eruption period C ended with the formation of Big Cinder Butte (figs. 2 and 4C), the largest cinder cone along the Great Rift. The bulbous, monolith-strewn Sawtooth, Indian Wells South, and Indian Wells North a'a flows were probably erupted from the slumped and broken southern part of Big Cinder Butte (fig. 5C).

We have been able to obtain a radiocarbon age only for the Sawtooth flows of eruption period C, thus we can not place limits on the beginning or the end of the interval. We suspect that most of the earlier group of pahoehoe-a'a flows (Sentinel, Fissure Butte, Sheep Trail Butte, South Echo) were erupted within a short period of time, probably less than 100 years. The time interval between the eruption of the pahoehoe-a'a group of flows and the later a'a group of flows is unknown, but we estimate it to be several hundred years or less.

Eruption period B

Black Top Butte (also called Blacktail Butte), the southeasternmost cinder cone along the Great Rift in the Craters of the Moon lava field (fig. 2), probably formed early in eruption period B and it is probably the source vent for the Rangefire flows (fig. 4B). Fluid pahoehoe erupted from obscure vents along the Great Rift about 10 km southeast of Black Top Butte cinder cone and formed the voluminous, composite Larkspur Park-Minidoka flows. A small dribble spire and a few small depressions occur at the apex of the lava cone and an extensive system of lava tubes and rootless vents radiates away from the buried vent complex for the Larkspur Park-Minidoka flows. A broad lava cone at Devils Cauldron (fig. 2), the source vent for the Devils Cauldron flows (fig. 4B), is indented by two, steep-sided vents that contained lava lakes. Eruptive fissures paralleled by spatter ramparts and thin blankets of tephra extend as much as 9 km northeast and southeast of Black Top cinder cone. The fissures are the source vents for the fissure-fed Deadhorse and Vermillion Chasm shelly pahoehoe flows (fig. 4B). These flows appear dusty brown, altered, and anomalously old due to weathering of their thin, highly vesicular crusts.

The radiocarbon data of Table 1 illustrate the imprecise nature of our attempts to date even young eruptions. Both the oldest flows (Range-fire) and next to youngest flows (Deadhorse) of eruption period B have radiocarbon ages of about 4,500 to 4,300 yrs. b.p. However, flows of intermediate age, based on stratigraphic relations, have radiocarbon ages for soils treated by the alkali-acid method of about 3,600 yrs. b.p. (Table 1). We do not know whether the ages for the Range-fire and Deadhorse flows are correct and the ages for the Devils Cauldron and Minidoka flows are too young, or whether the ages for the Deadhorse and Range-fire flows are too old. The fact that most ages on soils are minimum ages leads us to suspect that the 4,300-4,500 year ages are correct and that the 3,500-3,600 year ages are too young. The paleomagnetic and stratigraphic data and field relations indicate that all flows that we assign to eruption period B are tightly grouped in both time and space; they probably were erupted within a period of a few hundred years or less. We thus speculate that eruption period B began about 4,500 years ago and lasted for about 200-300 years.

Eruption period A

We do not have radiocarbon ages for critical flows that formed in eruption period A, such as the Highway, Devils Orchard, Serrate, Big Craters, and North Craters flows, but the stratigraphic order for flows of period A shown in Table 4 is reasonably well-known from field relations. The absolute age of the Highway-Devils Orchard-Serrate group of a'a and block lava flows is unknown, but we assume that the group formed no more than a few hundred years before the next youngest flows (Big Craters). We therefore include the Highway-Devils Orchard-Serrate group of flows as part of eruption period A. Paleomagnetic intensity measurements suggest that the Highway flow was erupted during a peak of geomagnetic field intensity about 2,300 years ago. We can not, however, discount the possibility the Highway-Devils Orchard-Serrate group of flows is considerably older, possibly as much as several hundred or several thousand years, and represents a separate eruption period unrelated to the younger group of dominantly pahoehoe flows (Big Craters, North Crater, Blue Dragon) that are known to be part of eruption period A.

The sequence of events that led to the eruption of the Highway-Devils Orchard-Serrate flows is extremely difficult to decipher in the field. At present, we still disagree among ourselves about the sequence of events even after many days of careful field work. We present here two possible scenarios for the formation of the Highway-Devils Orchard-Serrate group of flows. Additional field studies may help us to choose among and refine some of the ideas presented here.

In the first scenario, we suggest that eruption period A began about 2,300 years ago with eruptions in North Crater that produced a viscous, block lava flow (Highway) that flowed northward down the flanks of North Crater into the valley between Sunset Cone and Grassy Cone (figs. 2 and 4A). The eruptions were accompanied by the foundering of the north flank of North Crater and by formation of the "highway fault" (fig. 2). The highway fault is an arcuate, steep scarp, 1 to 10 m high, that may be a segment of a ring fracture formed by the collapse of the north flank of North Crater. The Highway flow reversed its direction of flow back toward North Crater after the "highway fault" formed and after the north flank of North Crater collapsed. Continuation of the eruption produced additional a'a and block flows that formed the Devils Orchard and Serrate flows. The Devils Orchard and Serrate flows are strewn with monoliths that were carried away from the slumped and broken northern flank of North Crater. The Highway-Devils Orchard-Serrate flows may represent eruption of successively less silicic lavas as described farther on. The high viscosity of the Highway flow (~63% SiO₂) may have caused so violent an eruption that it destroyed much of North Crater. The subsequent Devils Orchard (~61% SiO₂) and Serrate (~58% SiO₂) flows were viscous enough to raft large blocks of broken walls of North Crater for distances of several km.

In the second scenario, we suggest that the Highway flow formed as a steep sided tholoid in the area between Grassy Cone and Sunset Cone (figs. 2 and 4A). Evidence for a vent beneath the northern part of the Highway flow is weak, but viscous lava may well have built up over the vent and obscured it. The southern edge of the tholoid flowed to the south toward North Crater and over the scarp of the "highway fault", whose formation preceded and was unrelated to the formation of the tholoid. The later stages of the eruption then took place in or near North Crater, where viscous lava tore apart the northern flank of North Crater and formed the Devils Orchard and Serrate a'a-block flows (fig. 4A).

The youngest eruptions in the Craters of the Moon lava field occurred about 2,100 years ago (Table 1). These eruptions were mainly from fissures and cinder cones at Big Craters in the northern part of the Great Rift in the area between Inferno Cone and North Crater (figs 2 and 4A). The pahoehoe lava erupted from the Big Craters vents has a characteristically greenish-brown glassy crust. Eruptive fissures in the Trench Mortar Flat area between Big Cinder Butte and The Watchman cinder cones (fig. 2) formed flanking spatter ramparts and thin flows of gas-charged shelly pahoehoe. Voluminous eruptions of pahoehoe lava with iridescent blue glassy crusts (Blue Dragon flows) then occurred from fissures and lava domes located south of Big Craters (Fig. 4A). Most of the lava erupted from this locality flowed to the east through a series of large lava tubes. Much of the lava in the distal parts of the Blue Dragon flows was erupted from rootless vents along the lava tubes. The youngest eruptions in the Craters of the Moon lava field occurred from obscure vents on the east side of Broken Top cinder cone (figs. 2 and 4A).

Radiocarbon and paleomagnetic data indicate that lava flows of the Kings Bowl and Wapi lava fields are coeval and formed about 2,250 years ago. Inasmuch as paleomagnetic samples from all parts of the Wapi flow show the same paleomagnetic field directions, we suggest that the entire Wapi lava field formed in a matter of a few months or, possibly, a few years, but certainly not more than 10 years. Whole-rock chemical data, discussed in later sections, show that the Wapi and Kings Bowl lavas are distinctly different from their closest compositional and temporal counterparts in the the Craters of the Moon lava field. The Kings Bowl and Wapi lavas thus represent eruptions from a magma source that is unrelated to the source of lavas of the Craters of the Moon lava field.

KING'S BOWL AND WAPI LAVA FIELDS

The Kings Bowl lava field and its associated rift set are located along the southern part of the Great Rift, nine km southeast of the southeastern limit of the Craters of the Moon lava field (figs. 2 and 4A). The Kings Bowl lava field consists of about 0.01 km^3 of pahoehoe lava flows that cover an area of about 3.3 km^2 . The lavas were erupted about $2,220 \pm 100 \text{ yr b.p.}$ (Table 1) from the 7 km-long Kings Bowl segment of the Great Rift. The Kings Bowl rift set consists of a $N 10^\circ W$ -trending central eruptive fissure, flanked by two subparallel, noneruptive sets of cracks that lie 600 to as much as 1,100 m from the main eruptive fissure. The flanking crack sets are older than the central fissure, they are typically less than 1 m wide, and they record an extended history of opening. Basalt flows of Pleistocene age that are crossed by the cracks display varying degrees of crack development, and in several localities, cracks terminate against Holocene basalt flows. The central eruptive fissure is a system of discontinuous linear and en echelon cracks, each 2 to 3 m wide. In a few areas the central fissure is filled with breccia and feeder dikes, at other localities it is open. The central fissure divides into two subparallel, non-eruptive fissures 100 m to 200 m apart for a distance of one km at the northern end of the Kings Bowl rift set.

The Kings Bowl rift set is marked by spatter ramparts, small spatter cones, and explosion pits. Large spatter cones and spatter ramparts occur adjacent to explosion pits at South Grotto and Creon's Cave (fig. 2). Light-colored blankets of lapilli tephra spread eastward from these explosion pits. The largest explosion pit on the King's Bowl rift is King's Bowl, 85m long, 30 m across, and 30 m deep (King, 1977). A tephra blanket that covers an area of 0.15 km^2 extends up to 1.2 Km east of King's Bowl. The Kings Bowl lava field is characterized by low relief, thin (typically $<0.2 \text{ m}$), shelly pahoehoe lava flows that aggregate no more than 5 m, lava lakes, and low natural levees.

The Wapi lava field (Champion, 1973; Champion and Greeley, 1977) is a low shield volcano that covers an area of about 330 km^2 . Flow thicknesses near the edge of the field are about 1 to 10 m and near the source vent the flows are probably as much as 100 m thick. The lava field has a volume of approximately 11 km^3 . The volume of the Wapi lava field has been calculated by assuming a conical shape, a height of 100 m, and a base with a radius of 10 km. (Table 3). Based on well-studied Hawaiian eruptions (Swanson and others, 1971) and our paleomagnetic data, this volume of lava was probably erupted during a period lasting several weeks or months to possibly as much as several years.

The flows in the Wapi lava field display two characteristic surface morphologies. Slab pahoehoe has been formed into pressure ridges, pressure plateaus, tumuli, and sag depressions over most of the surface of the lava field. In the vicinity of Pillar Butte, the source vent area of the lava field, shelly pahoehoe and a'a flows that consist of broken plates of shelly pahoehoe have formed along with lava channels, lava gutters, and some lava tubes. The two lava types erupted simultaneously; both lava types overlap each other (Champion and Greeley, 1977). The age of the Wapi lava field has been obtained by two methods. A radiocarbon age of $2,270 \pm 50$ yrs. b.p. (S. Robinson, USGS, written commun., 1980) has been obtained for charcoal from beneath the flow. Additionally, nearly identical paleomagnetic measurements on samples from the Wapi and Kings Bowl lava fields (Champion and Greeley, 1977), in conjunction with the radiocarbon age of $2,220 \pm 125$ yrs. b.p. for the Kings Bowl lava field, indicate that the two lava fields formed nearly simultaneously over a short period of time.

VOLUME OF LAVA AND RATES OF ERUPTION

Figure 5 is a plot of cumulative volume of lava versus age for the

Figure 5--near here

eight eruption periods for the Craters of the Moon lava field. For periods D through A, the cumulative volume of nonevolved ($<50\% \text{ SiO}_2$) lava and nonevolved plus evolved ($>50\% \text{ SiO}_2$) lava are both plotted. Errors for the volumes of lava and the age and duration of each eruption period, as described previously, are incorporated into the figure. We assume that the area, height, and volume estimates of Table 3 may each be in error by as much as 50% and that overestimates and underestimates of volume probably cancel each other out in determining the total volume for each eruption period. We thus plot a 50% error in the estimate of the total volume for each eruption period and assume that errors in volume estimates are not cumulative from one eruption period to the next. The plots in figure 5 lead to the conclusion that long-term eruption rates of nonevolved lavas has been remarkably uniform at about $1.6 \text{ km}^3/1,000 \text{ years}$ for the last 15,000 years and that the eruption rate of the nonevolved lavas has also been remarkably uniform at about 1.2 km^3 for the last 7,000 years. The average total eruption rate for the last 7,000 years has been about $2.8 \text{ km}^3/1,000 \text{ years}$, which reflects the cumulative eruption rates of nonevolved and evolved lavas. The volume of lava actually erupted in any eruption period has been governed by at least 2 factors: 1) the length of repose time between the eruption and the preceding eruption, and 2) the long-term eruption rates.

The change in the eruption rate occurred about 7,000 years ago at a time when the composition of the Craters of the Moon lavas began to undergo a wide divergence (fig. 6). After that time, lavas of high silica,

Figure 6--near here

intermediate, and low silica compositions were erupted nearly simultaneously in several eruption periods. As discussed in detail farther on, the compositional variations in the lavas, in addition to the change in total eruption rate, lead us to speculate that the crust was heated to temperatures of partial melting about 7,000 years ago and that compositional variations in the erupted lavas since that time may be partly explained as due to mixing of various proportions of basaltic and granitic components or by derivation of magmas of variable compositions by partial melting of the crust. Such processes are not contradicted by available isotopic and trace element data for Craters of the Moon lavas (Leeman and others, 1976; Stout and Nicholls, 1977). However, Leeman and others (1976) and Stout and Nicholls (1977) have also shown that crystal fractionation of the phenocryst phases present in the primitive basalts may also be an important factor in producing evolved lavas.

COMPOSITIONAL RELATIONS AMONG LAVAS

Basaltic lavas erupted from vents along the Great Rift range in composition from primitive, iron-, alkali-, and phosphorous-rich tholeiitic basalts to trachyandesites in the terminology of Cox and others (1979). The rocks have a total silica range from 44% to 64%. Phenocrysts and microphenocrysts of olivine ($\text{Fo}_{80}\text{-Fo}_{40}$), plagioclase ($\text{An}_{70}\text{-An}_{40}$), titanomagnetite, ilmenite, and apatite occur in the glassy matrix of the more mafic rocks. Plagioclase, titanomagnetite, ilmenite, and rare, high-temperature, alkali feldspar are phenocrysts and microphenocrysts in the more silicic rocks. Clinopyroxene (augite-ferroaugite) occurs as subhedral to anhedral crystals in the matrix of rocks of various compositions. The petrography and petrogenesis of the lavas from the Great Rift are summarized in superb papers by Leeman and others (1976) and Stout and Nicholls (1977). Both of these studies speculate that primary magmas were derived by partial melting of lherzolite in the asthenosphere at depths of 40-60 km and that more evolved lavas were derived from the primary magmas by crystal fractionation of observed phenocryst phases at pressures of about 8-10 kbar, corresponding to depths of about 30 km.

We have compiled 143 bulk chemical analyses of lavas from the Craters of the Moon, Kings Bowl, and Wapi lava fields. Of this total, 45 analyses were previously published (Leeman, 1974; Stout, 1975), and we have obtained 102 additional analyses. Table 5 lists average chemical compositions for flows

Table 5--near here

within each of the eight eruption periods. Some of the older analyses represented in the average analyses in Table 5 are of variable quality, but the averages reflect broad changes and trends in lava composition within and between eruption periods. The average analyses are used here primarily for their comparative value, more detailed investigations of the petrochemistry and mineralogy of Great Rift lavas will be reported later.

The lavas of eruption period H are among the most mafic, least evolved lavas erupted from vents along the Great Rift; they are lower in SiO_2 , MgO , and CaO , but higher in total iron, total alkalis, and P_2O_5 when compared to average olivine tholeiites for the eastern Snake River Plain (Table 5).

The Lava Creek flows of eruption period G, like the lavas of period H, also represent some of the most mafic, least evolved lavas erupted from vents along the Great Rift (Table 5). They are particularly low in SiO_2 , and high in TiO_2 and total iron when compared to average olivine tholeiites of the eastern Snake River Plain (Table). It is interesting that other investigators have noted that the most evolved lavas in the Snake River Plain occur near its northern boundary (Stone, 1970; Leeman and others, 1976), yet the Lava Creek lavas erupted from vents located several km north of the northern margin of the ESRP are among the least evolved, most primitive lavas in the entire Snake River Plain. Lavas with compositions as primitive as those of eruption period H and the Lava Creek flows were erupted along the Great Rift at only one later time in eruption period C.

The average analyses of the Sunset and Carey flows of eruption period G are nearly identical, a fact that reinforces our interpretation that these flows represent eastern and western lobes of flows erupted from a source vent at Sunset Crater cinder cone. The large volume and area covered by the flows of period G (Table 5) are mainly represented by the Sunset and Carey flows.

The Lava Point lavas of eruption period E are dominantly bulbous a'a flows whereas the Grassy Cone and Laidlaw Lake flows are dominantly pahoehoe flows. The Lava Point flows have an average composition that is distinctly different than the average composition of the a'a flows of eruption periods D, C, and A. The younger a'a flows are mainly basaltic andesite, trachyandesite, or andesite in the terminology of Cox and others (1979) and they have higher SiO_2 contents and much lower TiO_2 , MgO , CaO , and P_2O_5 contents than the average composition of the Lava Point flows (Table 5). The Lava Point flows are basalt in the terminology of Cox and others (1979) and their average composition is much like that of typically fluid pahoehoe basalt of eruption periods G and F, thus the a'a texture of the Lava Point flows is probably related to such factors as the gas content of the lava, the roughness of the terrain over which the flows moved, and characteristics of its eruption processes. The Laidlaw Lake and Grassy Cone flows show a trend from older, more evolved lava to younger, less evolved lava, suggesting that a magma reservoir that was stratified by crystal fractionation was erupted from top to bottom.

The a'a lavas of eruption period D show the first significant trend toward more evolved lavas in the late Pleistocene-Holocene history of eruptions along the Great Rift, approximately at the time at which the long-term eruption rate doubled. The a'a lavas are characterized by SiO_2 contents of about 50 percent or greater and total alkali contents greater than six percent. Although the data are scanty, the chemical analyses suggest that the a'a lavas were erupted in a trend that reflects either progressive addition of silicic partial melt to a "parent magma" of about 50% SiO_2 or increased amounts of fractionation. Another factor that may account for the compositional trends may be the eruption of two lava types, one with a range of about 49 to 53% SiO_2 that is similar to the most evolved lavas of eruption period E and the other type with a silica percentage of about 58%.

The a'a lava flows of eruption period D were all probably erupted from Silent Cone on the northwestern part of the Great Rift, a locality that is near the source vents of subsequent high- SiO_2 a'a and block flows. Evidently that part of the Great Rift has been able to tap, via its own unique plumbing system, a magma reservoir that has undergone various degrees of crystal fractionation or magma mixing.

The earliest fissure eruptions of period C (Sentinel, Fissure Butte, Sheep Trail Butte, South Echo flows) produced fluid, mafic lavas that have average compositions similar to the average composition of the lavas of eruption period H and the Lava Creek lavas (Table 5). The fissure flows were followed by the more silicic Sawtooth and Indian Wells north and Indian Wells south a'a flows. Although we do not have radiocarbon ages for the early fissure flows of eruption period C, we suspect that they are only a few hundred years older than the later a'a flows, thus both very mafic and very silicic lavas were erupted from vents spaced only a few km apart along the Great Rift over a period of about several hundred years. The southern fissure vents apparently tapped a new supply of nonevolved magma and the more northerly vent at Big Cinder Butte appears to have tapped a supply of evolved magma that was nearly identical to the magma erupted in the later stages of eruption period D (fig. 6, Table 5).

The large-volume pahoehoe flows erupted mainly from fissure vents along the southern part of the Craters of the Moon segment of the Great Rift during eruption period B have average chemical compositions that are intermediate when compared to mafic lavas such as the Lava Creek flows and silicic lavas such as those of the Sawtooth a'a flows (Table 5). The flows of eruption period B show a general trend from older, more evolved lavas to younger, less-evolved lavas (fig. 6). This trend is also seen within the group by comparing the older Larkspur Park flows with the younger Minidoka flows, both of which were probably erupted within a short period of time from the same vent. The compositional trends suggest eruption of an evolved, stratified magma source from top to bottom. The large-volume Minidoka and Devils Cauldron lavas may represent the parent magma for the Rangefire and Larkspur Park flows and the Vermillion Chasm and Deadhorse flows may represent the magma that was enriched

in fractionated phases. (Table 5, fig. 6).

The lavas of eruption period A show a range in composition that is related to lava type, age, and location of vents. As described previously, we have no accurate field, radiocarbon, or paleomagnetic data that allows us to determine the order of eruption for the Highway-Devils Orchard-Serrate flows but an eruption sequence from early, evolved lavas (Highway) through younger, less evolved lavas (Devils Orchard followed by Serrate) is reasonable in terms of expected compositional trends. The a'a-block flows were followed by flows that form part of an increasingly more mafic lava sequence, from the Big Craters flows through the Broken Top flows. All of these flows were erupted from vents spaced no more than 4 km apart along the Great Rift.

The Wapi and King's Bowl lavas show the highest contents of MgO and CaO and the smallest contents of K₂O and Na₂O of all the Great Rift lavas, thus they may be considered, along with the Lava Creek lavas, to be the least evolved of all the lavas erupted from vents on the Great Rift. Many significant differences are apparent when comparing the two large-volume, pahoehoe-type lavas that were erupted from different ends of the Great Rift about 2,100-2,200 years ago. Wapi-Kings Bowl lavas are significantly lower in SiO₂, P₂O₅, total iron, and total alkalis and significantly higher in MgO and CaO when compared to the Blue Dragon lavas, thus it seems reasonable to assume that the two lava types are unrelated and erupted from different magma sources (fig. 6, Table 5). The Wapi-Kings Bowl lavas are similar to other primitive, unfractionated olivine tholeiites of the eastern Snake River Plain (Table 5) and the Blue Dragon lavas represent slightly evolved lavas. The trend from early, more evolved lavas to later, less-evolved lavas again suggests eruption from a stratified magma source from top to bottom.

CONCLUSIONS AND SPECULATIONS OF FUTURE ERUPTIONS

Some general conclusions can be reached from the age, volume, and composition data for lavas from the Great Rift. Gravity and magnetic data analysed by D. R. Mabey and colleagues (see Kuntz and others, 1980) indicate that a granitic pluton is present in the upper crust beneath the Craters of the Moon segment of the Great Rift. The geophysical data indicate that the top of the pluton is about 1 to 3 km below sea level, that its base is about 10.5 to 11.5 km below sea level, and that it extends laterally as far southeast as the southeastern limit of the Craters of the Moon lava field. Perhaps the density and viscosity of the lower crustal source region beneath the intrusive body increased due to the removal of the partial melt that formed the pluton in the upper crust, thus forming a lid in the lower crust that impedes the rise of magma. Crystal fractionation of nonevolved magma may thus take place at the base of the depleted crust at a depth of about 40-45 km, a depth that is in accord with the experimental data that supports fractionation at pressures of about 10 kbar (Leeman and others, 1976; Stout and Nicholls, 1977). The degree of fractionation of magma is dependent on the length of time of retention, which may be controlled by rate of stretching of the upper crust or to a threshold volume of magma which, when exceeded, creates a bouyant strain that exceeds the strength of the crust above the holding reservoir.

Highly evolved lavas have erupted only from the western side of the northern part of the Great Rift from vents at Silent Cone and Big Cinder Butte. The highly evolved lavas have an aggregate volume of only about 1.5 km³, the largest is the Sawtooth flow, 0.6 km³. These relations suggest that derivation of lavas more silicic than basalt by partial melting of the crust or a storage reservoir of evolved lava derived from fractionation of parent basalt magma was limited to the crust beneath the northwestern part of the Great Rift. The eruption rate and compositional variation data presented here support and equally plausible explanation for increased eruption rates and more silicic lavas after 7,000 years ago. We propose that the increased eruption rates and the addition of more silicic lavas to the average flux of more primitive basalt can be explained by heating of crustal rocks to partial melting temperatures that were reached about 7,000 years ago. This idea presents many models for the formation of a wide range of magma compositions by magma mixing, varying degrees of partial melting of crustal rocks of variable composition, and crystal fractionation of both primitive basalt and more silicic magmas. We plan to investigate these models and present our results in a later paper.

The large lava flows of the Craters of the Moon lava field (Blue Dragon, Minidoka-Larkspur Park, Sunset-Carey, Grassy-Laidlaw Lake, and Lava Point) are only slightly evolved lavas with compositions that are relatively to nonevolved olivine tholeiites of the eastern Snake River Plain (Table 5); they have undergone little fractionation or admixture with more silicic magmas. The fact that both evolved and nonevolved lavas were erupted nearly simultaneously in some eruption periods suggests that the plumbing system of the Great Rift was capable of tapping magma of various compositions in reservoirs at various levels or lateral positions beneath the Great Rift or that the plumbing system tapped fractionated reservoirs of limited extent (probably dike-like) at the same crustal level. For the latter case, the eruption of approximately 5 km^3 of sequentially less evolved lavas in some of the later eruption periods from vents spaced about 10 km or less in length along the volcanic rift zone give some numerical perspective on the shapes of the magma reservoirs. Such eruptions may represent the emptying of dike-like reservoirs with lengths of about 10 km, widths on the order of a few tens of meters and heights of a few tens of km.

If eruption, or actually the vertical propagation of the dike-like magma reservoir, is related to regional extension, then eruptions occur when the magma pressure created by buoyancy and intrusion exceeds the sum of the lithostatic pressure and the strength of the roof rocks, the latter being a function of the stored extensional strain (Lachenbruch and Sass, 1978; Bacon, 1981, written communication). Figure 4 shows that eruptions on the Craters of the Moon segment of the Great Rift have taken place on discrete sections, each about 10 km long or less, that are widely separated from earlier eruptive sections. The widely dispersal of the eruptive sections for successive eruption periods suggests that it takes tens of thousands of years for stored extensional strain to build up before being relieved by dike injection, thus this factor might be used to predict the site of future eruptions.

Although it is speculative to predict future eruptions based on the past history of a volcano or volcanic rift zone, the time and volume relations shown in figure 5 and the compositional trends listed in Table 5 and shown in figure 6 suggest that an eruption of about 5 km^3 of lava might occur within a few hundred years from vents located on the northern end of the Great Rift near Sunset Cone and the Lava Creek vents, or possibly near Silent Cone and Grassy Cone. These localities are sites where stored extensional strain may have built up to the point where it can be relieved by intrusion of dikes; they are parts of the Great Rift farthest removed from areas affected by of recent eruption. Eruptions from potential vents near Sunset Cone and the Lava Creek vents would likely produce slightly evolved lavas that would produce large volume pahoehoe flows. Eruptions from potential vents near Grassy Cone and Silent Cone might produce highly evolved lavas and potentially violent types of eruptions like those that took place in North Crater, Silent Cone, and Big Cinder Butte. That eruptions might occur simultaneously elsewhere along the Great Rift, such as in the vicinity of the King's Bowl and Wapi lava fields, seems remote when based on the record of volcanism for the entire length of the Great Rift.

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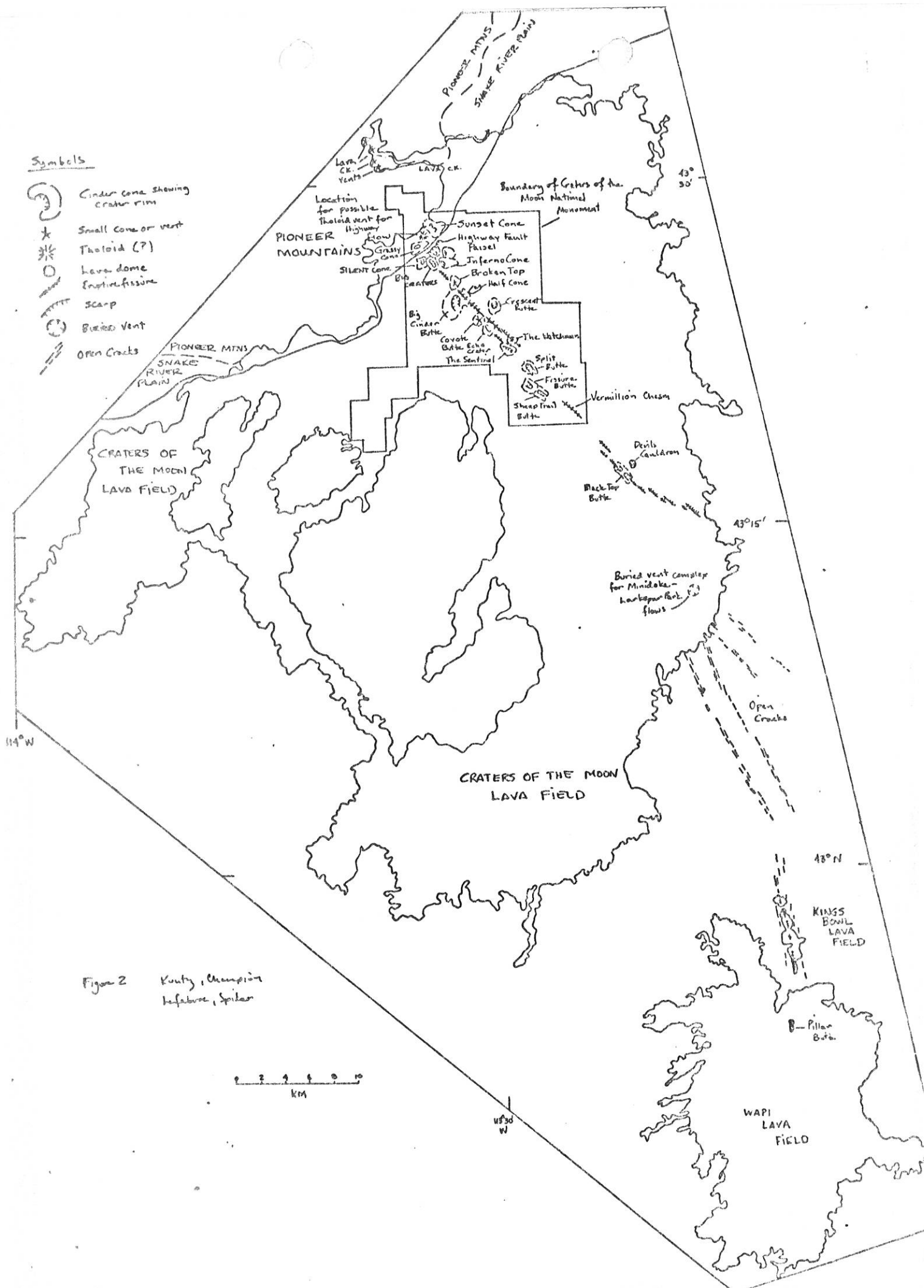


Figure 2 Kuntz, Champion before, Spiller

Figure 3 Kutz, Champion, Lefebvre, Spicer

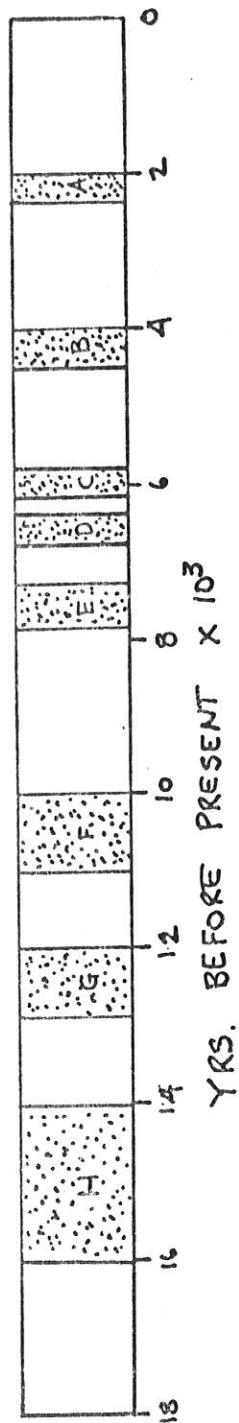
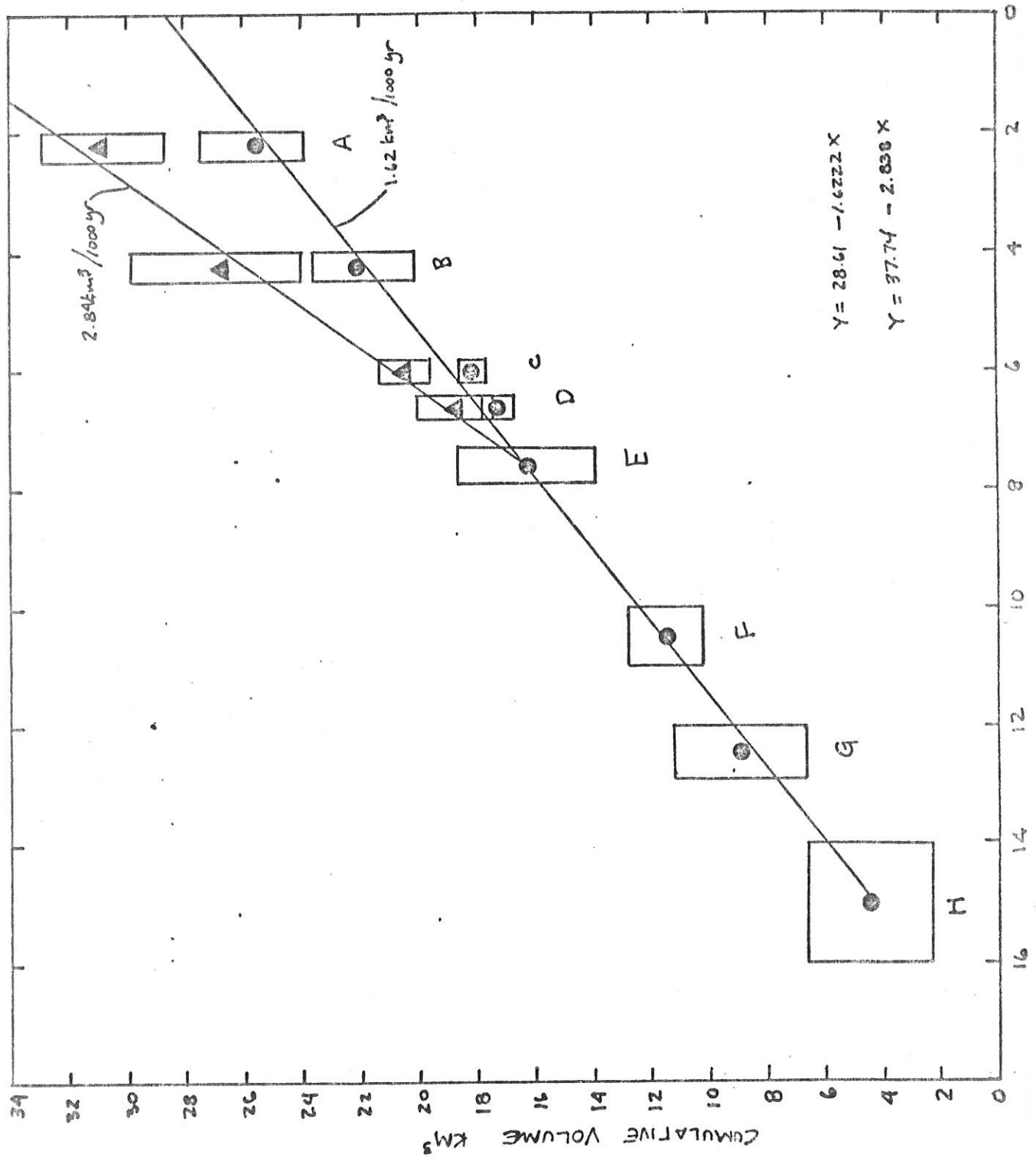


Figure 4 Kutz, Champion Lake, Lake Superior



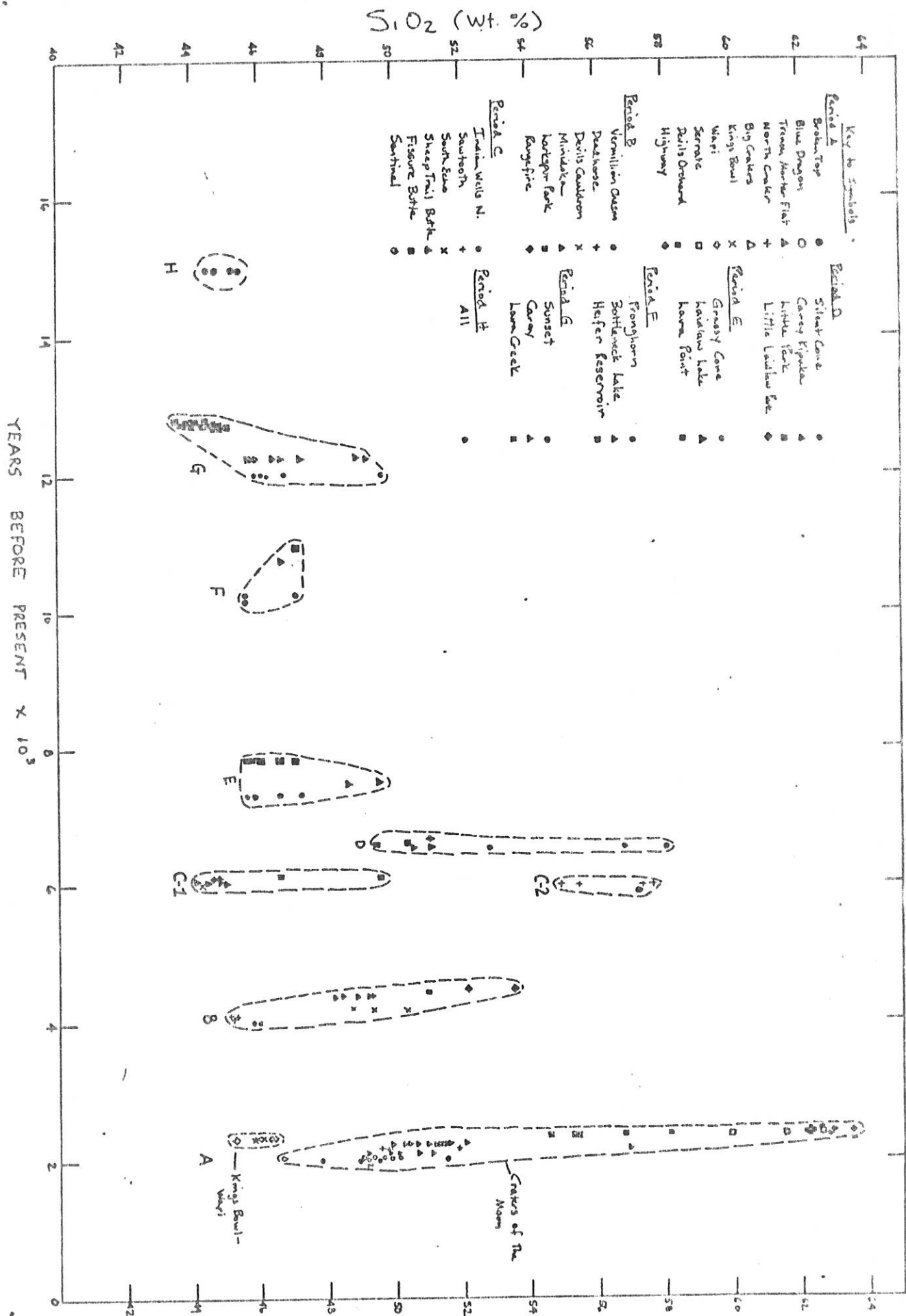


Table 1.--Radiocarbon ages of lava flows in the Craters of the Moon, Wapi, and Kings Bowl la- fields.

[For type of sample: s = untreated organic soil; s-a = organic soil treated by alkali-acid treatment described in text, c = untreated charcoal; c-a = charcoal treated by alkali-acid treatment described in the text. For lab. number, prefix Tx refers to University of Texas samples collected by Fred Bullard and analysed by Valastro and others (1972); prefix W refers to samples collected and analysed at the U.S.G.S. Radiocarbon Laboratory, Reston, VA.]

Eruption Interval and lava flows	Type of sample	Field number	Lab. number or reference	Radiocarbon age	Minimum age
Interval A					
Blue Dragon	c-a	K79-C5	W-4578	2,030±80	2076±45
	c	-	Tx-899	2,110±90	
	c	-	Tx-900	2,050±80	
	c	-	Tx-901	2,200±130	
Trench Mortar Flat	c-a	K79-C3	W-4413	2,100±60	2,205±25
	c	-	Tx-1157	2,210±80	
	c	-	Tx-1158	2,240±80	
	c	-	Tx-1159	2,250±80	
	c	-	Tx-1160	2,310±70	
	c	-	Tx-1161	2,130±80	
	c	-	Tx-1162	2,270±80	
	c	-	Tx-1163	2,140±60	
	c-a	K79-C6	W-4581	2,180±70	
Kings Bowl	c	-	Tx-1164	2,090±470	2,222±100
	c	-	Tx-1165	2,360±150	
	-	-	Prinz (1970)	2,130±130	
Wapi	c	-	-	2,270±50	2,270±50
Interval B					
Deadhorse	s	K78-S55	W-4259	4,300±60	4,300±60(?)
Devils Cauldron	s	K78-S56	W-4287	2,820±90	3,660±60
	s-a	K78-S56	W-4439	3,660±60	
Minidoka	s	K78-S58b	W-4267	2,650±50	3,190±70
	s-a	K78-C7	W-4447	3,590±70	
Range-fire	s-a	K78-S58a	W-4742	4,510±100	4,510±100
Interval C					
Sawtooth	s-a	K78-S67	W-4370	6,020±160	6,020±160
Interval D					
Carey Kipuka	s	K78-S64	W-4310	3,860±120	6,600±60
	s-a	K78-S64	W-4592	6,600±60	
Little Park	s	K78-S66	W-4260	3,960±90	6,500±60
	s-a	K78-S66	W-4587	6,500±60	
Interval E					
Grassy Cone	s-a	K78-S60	W-4385	6,670±100	7,360±60
	s-a	K79-C12	W-4488	7,360±60	
Laidlaw Lake	s-a	K79-C9	W-4511	7,470±80	7,470±80
Lava Point	s-a	K78-S68	W-4497	7,840±40	7,840±40
Interval F					
Pronghorn	s	K78-S73	W-4271	6,820±60	10,240±120
	s-a	K78-S73	W-4586	10,240±120	
Bottleneck Lake	s	K78-S72	W-4291	5,230±110	11,000±100
	s-a	K78-S72	W-4748	7,900±100	
	s	K78-S71	W-4280	10,890±120	
	s	K78-S71	W-4305	11,000±100	
Heifer Reservoir	s	K78-S53b	W-4306	9,330±120	10,670±150
	s-a	K78-S54	W-4583	10,670±150	
Interval G					
Sunset	s	K78-S58c	W-4270	3,270±80	12,010±150
	c	K76-C4A	W-3674	11,120±120	
	c-a	K78-S77	W-4296	12,010±150	
Carey	s	K78-S62	W-4235	4,310±80	12,000
	s	K78-S61	W-4301	6,500±110	
Lava Creek	s-a	K79-C11	W-4478	11,970±120	12,760±150
	s-a	K79-C10	W-4476	12,760±150	
Interval H					
Kinama	s-a	K78-S75	W-4387	13,900±400	15,100±160
	s-a	K79-C8	W-4473	15,100±160	

Table 2.--Paleomagnetic data for lava flows in the Craters of the Moon, Kings Bowl, and Wapi lava fields

Eruption period and map unit	Informal names of flows making up paleodirectional group (upper part of Snake River Group)	Number of sites	Kappa* (k)	c.s.d.* ()	alpha-95 (95)	Latitude of VGP* (degrees)	Longitude of VGP* (degrees)
A	Broken Top flows	2	1,227	2.31	7.14	79.45	186.37
	Blue Dragon flows	8	1,244	2.30	1.57	84.43	185.43
	Wapi-Kings Bowl flows	2	10,246	0.80	2.47	80.39	327.80
	Highway-Serrate flows	2	185	5.96	18.47	84.73	280.05
B	Vermillion Chasm flows	4	1,409	2.16	2.45	81.85	128.60
	Devils Cauldron flows	5	1,405	2.16	2.04	85.67	116.41
	Minidoka-Larkspur	3	1,816	1.90	2.89	86.88	98.40
	Park flows						
C	Range fire flows	3	1,755	1.93	2.94	84.36	87.50
	Indian Wells north and south, Sawtooth, Sheep Trail Butte, and Fissure Butte flows	6	2,028	1.80	1.49	79.71	236.14
	Sentinel flows	2	448	3.83	11.83	72.00	264.82
	Silent Cone, Carey	3	265	4.97	7.58	77.05	15.81
D	Kipuka, Little Park, Little Laidlaw Park,						
E	Grassy Cone-Laidlaw lake flows	4	3,376	1.39	1.58	83.69	132.24
	Lava Point flows	4	547	3.46	3.93	80.66	31.13
F	Pronghorn flows	7	1,701	1.96	1.46	79.29	352.32
	Bottleneck Lake flows	5	1,057	2.49	2.36	76.76	185.22
	Heifer Reservoir flows	2	120,279	0.23	0.72	83.20	95.20
G	Sunset-Carey flows	7	2,412	1.65	1.23	76.09	339.30
	Lava Creek flows	1	---	---	---	78.64	94.85
H	Kimama flows	1	---	---	---	85.84	57.52
	Bear Den Lake and other flows	3	904	2.69	4.10	75.66	64.36
	Unnamed flows	3	340	4.39	6.70	78.50	37.79

Abbreviations:

1. Kappa--statistical parameter, ranging from zero to infinity, that measures dispersion of measured field direction.
2. c.s.d.--radius of circle enclosing 63% of all data points.
3. alpha-95--radius of circle surrounding mean field direction, within which the mean field direction is located with a 95% statistical certainty.
4. VGP--virtual geomagnetic pole
-- no data

Eruption Period and flows	Estimated Area (km ²)	Average Thickness (cm)	Estimated Volume (km ³)
<u>Period A</u>			
Broken Top	11.2	10	0.11
Blue Dragon	281.0	12	3.37
Trench/Mortar Flat	5.9	5	0.03
North Crater	1.6	5	0.01
Big Craters	9.1	5	0.05
Kings Bowl	3.3	3	0.01
Wapi	326.0	75	
Serrate	20.8	20	0.41
Devil's Orchard	4.8	20	0.10
Highway	1.6	20	0.03
<u>Period B</u>			
Vermillion Cross	19.8	5	0.10
Deadhorse	8.4	5	0.04
Devil's Corridor	88.3	10	0.88
Minidoka	246.1	12	2.95
Larkspur Park	107.8	12	1.28
Range fire	103.3	10	1.03
<u>Period C</u>			
Indian Wells N	12.5	15	0.19
Indian Wells S	6.5	15	0.08
Sawtooth	37.5	15	0.56
South Echo	2.7	10	0.03
Shoof Trail	45.0	10	0.45
Fissure Butte	5.7	10	0.06
Sentinel	29.5	10	0.30
<u>Period D</u>			
Silout Cone	8.9	15	0.13
Carey Kipuka	38.4	15	0.58
Little Park	71.3	15	1.07
Little Laidlaw Fl	22.7	15	0.75
<u>Period E</u>			
Grassy Cone	118.4	10	1.18
Laidlaw Lake	150.5	10	1.50
Lava Point	131.4	15	2.09
<u>Period F</u>			
Pronghorn	83.1	10	0.83
Potters Lake	134.0	10	1.34
Heifer Reservoir	42.3	10	0.42
<u>Period G</u>			
Sunset	102.0	10	1.02
Carey	231.6	12	2.77
Lava Creek	68.3	10	0.68
<u>Period H</u>			
All	440.0	10	4.40

Table 4.--Eruption periods, approximate age of eruption periods, informal name of lava flows of upper part of Snake River Group and source vents for lava flows of the Craters of the Moon, Wapi, and Kings Bowl lava fields.

Eruption period and approx. age	Informal name and lava type of major flows*	Source vents (queried where uncertain)
A 2100 to 2300 yrs. b.p.	Broken Top (p)	Broken Top, east and south sides
	Blue Dragon (p)	Eruptive fissures south of Big Craters cinder cone
	Trench Mortar Flat (p)	Eruptive fissures between Big Cinder Butte and The Watchman cinder cone
	North Crater (p)	North Crater cinder cone
	Big Craters (Green Dragon) (p)	Eruptive fissure at north end of Big Craters cinder cone
	Kings Bowl (p)	Fissure vents north and south of Kings Bowl
	Wapi (p)	Vents at Pillar Butte
	Serrate (a-b)	North Crater (?)
	Devils Orchard (a-b)	North Crater cinder cone(?)
	Highway (a-b)	North Crater cinder cone(?) or tholoid vent(?) between Grassy Cone and Sunset Cone cinder cones
B 4000 to 4500 yrs. b.p.	Vermillion Chasm (p)	Eruptive fissures at Vermillion Chasm
	Deadhorse (p)	Eruptive fissures north and south of Black Top Butte cinder cone
	Devils Cauldron (p)	Devils Cauldron
	Minidoka (p)	Obscure vents located about 5 km northeast of New Butte cinder cone
	Larkspur Park (p)	Black Top Butte cinder cone (?)
C 5800 to 6200 yrs. b.p.	Range-fire (p)	Big Cinder Butte cinder cone(?)
	Indian Wells north (a)	Big Cinder Butte cinder cone(?)
	Indian Wells south (a)	Big Cinder Butte cinder cone
	Sawtooth (a)	Eruptive fissures south of Echo Butte cinder cone
	South Echo (p)	Sheep Trail Butte cinder cone
	Sheep Trail Butte (p-a)	Fissure Butte cinder cone
	Fissure Butte (p-a)	The Sentinel cinder cone
	Sentinel west (p)	The Sentinel cinder cone
	Sentinel south (p)	Silent Cone cinder cone
	Silent Cone (a)	Silent Cone cinder cone (?)
D About 6600 yrs. b.p.	Carey Kipuka (a)	Silent Cone cinder cone (?)
	Little Park (a)	Silent Cone cinder cone (?)
	Little Laidlaw Park (a)	Silent Cone cinder cone (?)
		Silent Cone cinder cone (?)
E 7300 to 7900 yrs. b.p.	Grassy Cone (p)	Grassy Cone cinder cone
	Laidlaw Lake (p)	Grassy Cone cinder cone
	Lava Point (a)	Great Rift northwest of Echo Crater
F 10,000 to 11,000 yrs. b.p.	Pronghorn (p)	Great Rift near Sheep Trail Butte
	Bottleneck Lake (p)	Great Rift near Sheep Trail Butte
	Heifer Reservoir (p)	Great Rift near Crescent Butte
G 12,000 to 12,900 yrs. b.p.	Sunset (p)	Sunset Cone cinder cone
	Carey (p)	Sunset Cone cinder cone
	Lava Creek (p-a)	Vents near Lava Creek
H About 15,000 yrs. b.p.	Kinama (p)	unknown
	Bear Den Lake (p)	unknown
	Baseline (p)	unknown
	Little Prairie (p)	unknown
	Lost Kipuka (p)	unknown
	No Name (p)	unknown
	Brown flow (p)	unknown
* (p)	chiefly pahoehoe flows	
	(a)	chiefly a'a flows
	(a-b)	a'a and block flows
	(p-a)	pahoehoe and a'a flows
		Echo Crater and (or) Crescent Butte (?)

Table 5. Average chemical analyses of lavas in the Craters of the Moon, Wapi, Kings Bowl, and Highway fields. [Numbers in parentheses refer to total number of samples for which average value calculated, analyses arranged from youngest to oldest with youngest to left in each eruption period]

Eruption Period A

	Broken Top	Blue Dragon	Trench Mortar Flat	North Crater	Rig Craters	Kings Bowl	Wapi	Serrate	Devils Orchard	Highway
	(4)	(8)	(6)	(3)	(12)	(3)	(3)	(6)	(5)	(7)
	49.69	49.08	51.27	50.37	51.00	45.85	45.98	58.22	60.89	63.25
	2.89	2.71	2.52	2.49	2.53	2.27	2.54	1.21	0.87	0.56
	13.51	13.83	13.89	13.99	13.93	14.94	15.59	14.17	14.67	14.57
	1.29	2.04	1.33	1.40	1.60	1.74	1.55	1.20	1.45	1.04
	14.41	13.61	12.57	14.11	13.34	11.10	11.06	9.92	8.73	7.24
	3.32	3.29	3.08	3.12	2.88	9.95	8.01	1.10	0.54	0.26
	7.22	6.89	6.68	6.77	6.62	10.20	10.49	4.08	3.62	2.96
	0.26	0.26	0.24	0.29	0.28	0.19	0.18	0.19	0.22	0.19
	3.44	3.59	3.70	3.50	3.50	2.53	2.72	4.02	4.08	4.13
	2.05	2.04	2.40	2.08	2.24	0.45	0.64	3.66	4.27	4.80
	1.92	1.68	1.59	1.53	1.61	0.57	0.69	0.55	0.32	0.11
	0.04	0.07	0.03	0.01	0.04	0.02	0.01	0.06	0.02	0.02
	0.16	0.74	0.13	0.23	0.29	0.16	0.15	0.30	0.16	0.24
	100.22	99.43	99.43	99.80	99.86	99.97	99.61	98.68	99.84	99.37

Eruption Period B

	Vermillion Chasm	Deadhorse	Devils Cauldron	Minidoka	Larkspur Park	Range-fire	Blacktop Butte
	(2)	(3)	(3)	(5)	(1)	(2)	(4)
	45.84	45.16	49.50	48.76	50.94	52.82	50.76
	3.22	3.17	2.82	2.89	2.45	2.12	2.56
	14.14	14.37	13.61	13.81	13.93	14.10	13.80
	1.77	0.75	0.92	1.19	0.78	1.75	1.64
	13.11	14.10	14.17	14.25	13.91	12.14	13.03
	5.99	6.33	3.40	3.61	2.86	2.22	2.97
	9.91	9.56	7.16	7.05	6.31	5.79	6.61
	0.24	0.25	0.24	0.24	0.22	0.24	0.22
	2.89	2.80	3.79	3.54	4.25	4.10	3.95
	1.23	1.17	2.08	2.02	2.34	2.72	2.29
	2.06	2.01	1.83	2.03	1.47	1.23	1.60
	0.03	0.06	0.08	0.08	0.15	0.02	0.06
	0.25	0.26	0.30	0.49	0.26	0.30	0.58
	100.68	99.99	99.90	99.96	99.87	99.55	100.07

Eruption Period C

	Indian Wells North	Sawtooth	South Echo	Sheep Trail Butte	Fissure Butte	Sentinel
	(1)	(4)	(1)	(4)	(2)	(2)
	57.50	56.29	44.27	44.55	48.10	44.70
	1.29	1.51	3.71	3.65	2.91	3.69
	15.11	14.67	14.12	13.56	13.38	13.44
	1.04	1.59	2.45	1.90	1.66	1.97
	10.23	10.51	14.18	14.35	14.18	14.31
	1.45	1.65	5.10	5.12	3.40	4.92
	4.12	4.61	8.16	8.85	7.51	9.56
	0.21	0.21	0.27	0.25	0.25	0.27
	3.97	4.07	3.36	3.21	3.40	3.05
	3.40	3.19	1.56	1.53	1.97	1.58
	0.62	0.77	2.83	2.52	2.00	2.69
	0.07	0.06	0.15	0.10	0.07	0.03
	0.43	0.17	0.19	0.29	0.43	0.48
	99.14	99.50	100.35	99.88	100.26	100.69

Eruption Period D

	Silent Cone	Carey Pipuka	Little Park	Little Laidlaw Park
	(3)	(2)	(2)	(1)
	55.84	50.79	49.88	51.03
	1.72	2.38	2.58	2.33
	13.95	14.31	14.34	13.84
	1.65	1.34	1.52	1.10
	10.54	13.01	13.33	13.00
	1.59	2.94	3.14	2.61
	4.96	6.21	6.44	6.42
	0.20	0.22	0.23	0.24
	3.70	4.28	4.04	3.66
	2.93	2.41	2.25	2.48
	0.94	1.42	1.75	1.48
	0.03	0.09	0.04	0.03
	0.35	0.65	0.57	0.28
	98.40	100.05	100.11	98.59

Eruption Period E

	Crassy Cone	Laidlaw Lake	Lava Point
	(4)	(2)	(5)
	46.32	49.14	46.20
	3.14	2.78	3.48
	12.98	13.43	13.46
	2.30	1.06	1.61
	14.81	14.12	14.34
	4.12	3.26	4.30
	7.86	6.99	7.96
	0.27	0.25	0.24
	3.33	3.44	3.23
	1.65	2.09	1.68
	2.26	1.90	2.40
	0.03	0.07	0.10
	0.47	0.39	0.57
	99.70	98.82	99.57

Eruption Period F

	Pronghorn	Bottleneck Lake	Heifer Reservoir
	(3)	(1)	(1)
	46.02	46.58	47.10
	3.19	3.33	3.50
	13.66	13.42	14.40
	1.29	1.35	1.60
	14.74	14.71	14.40
	4.09	4.21	4.40
	7.70	8.79	7.80
	0.26	0.27	0.21
	3.61	3.39	3.10
	1.89	1.83	1.60
	2.33	2.46	2.60
	0.07	0.00	0.01
	0.28	0.23	0.57
	99.13	101.17	101.29

Eruption Period G

	Sunset	Carey	Lava Creek
	(5)	(8)	(15)
	46.87	46.94	44.27
	3.12	3.10	3.86
	13.78	13.83	13.80
	2.57	1.31	2.23
	14.05	14.05	14.49
	3.84	3.80	5.07
	7.35	7.40	8.34
	0.29	0.25	0.27
	3.70	3.51	3.33
	2.02	2.01	1.58
	2.13	2.27	2.45
	0.03	0.04	0.09
	0.23	0.20	0.19
	99.98	99.61	99.97

Eruption Period H

	Kimama	Bear Den Lake	Little Prairie
	(2)	(1)	(1)
	45.32	44.46	44.46
	3.24	3.39	3.39
	14.22	12.89	13.84
	1.79	0.52	1.10
	14.66	15.43	14.40
	4.26	4.18	4.18
	7.65	8.99	7.65
	0.26	0.26	0.26
	3.35	3.11	3.11
	1.73	1.56	1.56
	2.62	2.76	2.76
	0.09	0.09	0.09
	0.88	0.35	0.35
	100.07	97.89	98.57

Lowest of all lavas, probably from the same source as the others, but with a different composition.

These lavas are of the same type as the others, but with a different composition.

These lavas are of the same type as the others, but with a different composition.

Table 5. Average chemical analyses of lavas in the Craters of the Moon, Wapi, Kings Bowl, and Highway fields. (Numbers in parentheses refer to total number of samples for which average value is calculated, analyses arranged from youngest to oldest with youngest to left in each eruption period)

Eruption Period A									
Broken Top	Blue Dragon	Trench Mortar Flat	North Crater	Rig Craters	Kings Bowl	Wapi	Serrate	Devils Orchard	Highway
(4)	(8)	(6)	(3)	(12)	(3)	(3)	(6)	(5)	(7)
49.64	49.08	51.27	50.37	51.00	45.85	45.98	58.22	60.89	63.25
2.89	2.71	2.52	2.49	2.53	2.27	2.54	1.21	0.87	0.56
13.51	13.83	13.89	13.99	13.93	14.94	15.59	14.17	14.67	14.57
1.29	2.04	1.33	1.40	1.60	1.74	1.55	1.20	1.45	1.04
14.41	13.61	12.57	14.11	13.34	11.10	11.06	9.92	8.73	7.24
3.32	3.29	3.08	3.12	2.88	9.95	8.01	1.10	0.54	0.26
7.22	6.89	6.68	6.77	6.62	10.20	10.49	4.08	3.62	2.96
0.26	0.26	0.24	0.29	0.28	0.19	0.18	0.19	0.22	0.19
3.44	3.59	3.70	3.50	3.50	2.53	2.72	4.02	4.08	4.13
2.05	2.04	2.40	2.08	2.24	0.45	0.64	3.66	4.27	4.80
1.92	1.68	1.59	1.53	1.61	0.57	0.69	0.55	0.32	0.11
0.04	0.07	0.03	0.01	0.04	0.02	0.01	0.06	0.02	0.02
0.16	0.34	0.13	0.23	0.29	0.16	0.15	0.30	0.16	0.24
100.22	99.43	99.43	99.89	99.86	99.97	99.61	98.68	99.84	99.37

Eruption Period B							Average change in composition from Period A		
Vermilion Chasm	Deedhorse	Devils Cauldron	Minidoka	Larkspur Park	Range-fire	Blacktop Butte	(1)	(2)	(3)
(2)	(3)	(3)	(5)	(1)	(2)	(4)			
45.84	45.16	49.50	48.76	50.94	52.82	50.76	45.84	47.72	48.76
3.22	3.17	2.82	2.89	2.45	2.12	2.56	3.22	3.17	2.82
14.14	14.37	13.61	13.81	13.93	14.10	13.80	14.14	14.37	13.61
1.77	0.75	0.92	1.19	0.78	1.75	1.64	1.77	0.75	0.92
13.11	14.10	14.17	14.25	13.91	12.14	13.03	13.11	14.10	14.17
5.99	6.33	3.40	3.61	2.86	2.22	2.97	5.99	6.33	3.40
9.91	9.56	7.16	7.05	6.31	5.79	6.61	9.91	9.56	7.16
0.24	0.25	0.24	0.24	0.22	0.24	0.22	0.24	0.25	0.24
2.89	2.80	3.79	3.54	4.25	4.10	3.95	2.89	2.80	3.79
1.23	1.17	2.08	2.02	2.34	2.72	2.29	1.23	1.17	2.08
2.06	2.01	1.83	2.03	1.47	1.23	1.60	2.06	2.01	1.83
0.03	0.06	0.08	0.08	0.15	0.02	0.06	0.03	0.06	0.08
0.25	0.26	0.30	0.49	0.26	0.30	0.58	0.25	0.26	0.30
100.68	99.49	99.90	99.96	99.87	99.55	100.07	100.68	99.49	99.90

Eruption Period C						Eruption Period D			
Indian Wells North	Sawtooth	South Echo	Sheep Trail Butte	Fissure Butte	Sentinel	Silent Cone	Carey Kipuka	Little Park	Little Laidlaw Park
(1)	(4)	(1)	(4)	(2)	(2)	(3)	(2)	(2)	(1)
57.20	56.29	44.27	44.55	48.10	44.70	55.84	50.79	49.88	51.03
1.29	1.51	3.71	3.65	2.91	3.69	1.72	2.38	2.58	2.33
15.11	14.67	14.12	13.56	13.38	13.44	13.95	14.31	14.34	13.84
1.04	1.59	2.45	1.90	1.66	1.97	1.65	1.34	1.52	1.10
10.23	10.51	14.18	14.35	14.18	14.31	10.54	13.01	13.33	13.00
1.45	1.65	5.10	5.12	3.40	4.92	1.59	2.94	3.14	2.61
4.12	4.61	8.16	8.85	7.51	9.56	4.96	6.21	6.44	6.42
0.21	0.21	0.27	0.25	0.25	0.27	0.20	0.22	0.23	0.24
3.97	4.07	3.36	3.21	3.40	3.05	3.70	4.28	4.04	3.66
3.40	3.19	1.56	1.53	1.97	1.58	2.93	2.41	2.25	2.48
0.62	0.77	2.83	2.52	2.00	2.69	0.94	1.42	1.75	1.48
0.07	0.06	0.15	0.10	0.07	0.03	0.03	0.09	0.04	0.03
0.43	0.17	0.19	0.29	0.43	0.48	0.35	0.65	0.57	0.28
99.14	99.30	100.35	99.88	100.26	100.69	98.40	100.05	100.11	98.50

Eruption Period E			Eruption Period F			Eruption Period G			Eruption Period H		
Grassy Cone	Laidlaw Lake	Lava Point	Prong-horn	Bottleneck Lake	Heifer Reservoir	Sunset	Carey	Lava Creek	Vinasa	Bear Den Lake	Little Prairie
(4)	(2)	(5)	(3)	(1)	(1)	(5)	(8)	(15)	(2)	(1)	(1)
46.32	46.14	46.20	46.02	46.58	47.10	46.87	46.94	44.27	45.32	44.46	45.32
3.14	2.78	3.48	3.19	3.33	3.50	3.12	3.10	3.86	3.24	3.39	3.24
12.98	13.43	13.46	13.66	13.42	14.40	13.78	13.83	13.80	14.22	12.80	13.78
2.30	1.06	1.61	1.29	1.35	1.60	2.57	1.31	2.23	1.79	0.52	1.79
14.81	14.12	14.34	14.74	14.71	14.40	14.05	14.95	14.49	14.66	15.41	14.05
4.12	3.26	4.30	4.09	4.21	4.40	3.84	3.80	5.07	4.26	4.18	4.12
7.86	6.99	7.96	7.70	8.79	7.80	7.35	7.40	8.34	7.65	8.98	7.35
0.27	0.25	0.24	0.26	0.27	0.21	0.29	0.25	0.27	0.26	0.26	0.29
3.33	3.44	3.23	3.61	3.39	3.10	3.70	3.51	3.33	3.35	3.11	3.33
1.85	2.09	1.68	1.89	1.83	1.60	2.02	2.01	1.58	1.73	1.56	1.73
2.26	1.90	2.40	2.33	2.46	2.60	2.13	2.27	2.45	2.62	2.76	2.13
0.03	0.07	0.10	0.07	0.60	0.01	0.03	0.04	0.09	0.09	0.09	0.03
0.41	0.39	0.57	0.28	0.23	0.57	0.23	0.20	0.19	0.88	0.35	0.23
99.20	98.92	99.37	99.13	101.17	101.29	99.98	99.61	99.97	100.07	97.89	98.20

Lava flows in the craters of the Moon, Wapi, Kings Bowl, and Highway fields.

Average chemical analyses of lavas in the craters of the Moon, Wapi, Kings Bowl, and Highway fields.

Analyses arranged from youngest to oldest with youngest to left in each eruption period.

Table 1.--Eruption periods, approximate age of eruption periods, informal name, lava flows of upper part of Snake River Group and source vents for lava flows in the Craters of the Moon, Wapi, and Kings Bowl lava fields.

Eruption period and approx. age	Informal name and lava type of major flows*	Source vents (queried where uncertain)
A 2100 to 2300 yrs. b.p.	Broken Top (p)	Broken Top, east and south sides
	Blue Dragon (p)	Eruptive fissures south of Big Craters cinder cone
	Trench Mortar Flat (p)	Eruptive fissures between Big Cinder Butte and The Watchman cinder cone
	North Crater (p)	North Crater cinder cone
	Big Craters (Green Dragon) (p)	Eruptive fissure at north end of Big Craters cinder cone
	Kings Bowl (p)	Fissure vents north and south of Kings Bowl
	Wapi (p)	Vents at Pillar Butte
	Serrate (a-b)	North Crater (?)
	Devils Orchard (a-b)	North Crater cinder cone(?)
	Highway (a-b)	North Crater cinder cone(?) or tholoid vent(?) between Grassy Cone and Sunset Cone cinder cones
B 3500 to 4500 yrs. b.p.	Vermillion Chasm (p)	Eruptive fissures at Vermillion Chasm
	Deadhorse (p)	Eruptive fissures north and south of Black Top Butte cinder cone
	Devils Cauldron (p)	Devils Cauldron
	Minidoka (p)	Obscure vents located about 5 km northeast of New Butte cinder cone
	Larkspur Park (p)	Black Top Butte cinder cone (?)
C 5800 to 6200 yrs. b.p.	Range fire (p)	Big Cinder Butte cinder cone(?)
	Indian Wells north (a)	Big Cinder Butte cinder cone(?)
	Indian Wells south (a)	Big Cinder Butte cinder cone
	Sawtooth (a)	Eruptive fissures south of Echo Butte cinder cone
	South Echo (p)	Sheep Trail Butte cinder cone
D About 6000 yrs. b.p.	Sheep Trail Butte (p-a)	Fissure Butte cinder cone
	Fissure Butte (p-a)	The Sentinel cinder cone
	Sentinel west (p)	The Sentinel cinder cone
	Sentinel south (p)	Silent Cone cinder cone
	Silent Cone (a)	Silent Cone cinder cone (?)
E 7300 to 7900 yrs. b.p.	Carey Kipuka (a)	Silent Cone cinder cone (?)
	Little Park (a)	Silent Cone cinder cone (?)
	Little Laidlaw Park (a)	Silent Cone cinder cone (?)
	Grassy Cone (p)	Grassy Cone cinder cone
	Laidlaw Lake (p)	Grassy Cone cinder cone
F 10,000 to 11,000 yrs. b.p.	Lava Point (a)	Great Rift northwest of Echo Crater
	Pronghorn (p)	Great Rift near Sheep Trail Butte
	Bottleneck Lake (p)	Great Rift near Sheep Trail Butte
	Heifer Reservoir (p)	Great Rift near Crescent Butte
G 12,000 to 12,900 yrs. b.p.	Sunset (p)	Sunset Cone cinder cone
	Carey (p)	Sunset Cone cinder cone
	Lava Creek (p-a)	Vents near Lava Creek
H About 15,000 yrs. b.p.	Kimina (p)	unknown
	Bear Den Lake (p)	unknown
	Baseline (p)	unknown
	Little Prairie (p)	unknown
	Lost Kipuka (p)	unknown
I * (p) (a) (a-b) (p-a)	No Name (p)	unknown
	Brown flow (p)	unknown
	chiefly pahoehoe flows	
	chiefly a'a flows	
	a'a and block flows	
	pahoehoe and a'a flows	
		Echo Crater and (or) Crescent Butte (?)

Table 1.--Eruption periods, approximate age of eruption periods, informal name of lava flows of upper part of Snake River Group and source vents for lava flows in the Craters of the Moon, Wapi, and Kings Bowl lava fields.

Eruption period and approx. age	Informal name and lava type of major flows*	Source vents (queried where uncertain)
A 2100 to 2300 yrs. b.p.	Broken Top (p)	Broken Top, east and south sides
	Blue Dragon (p)	Eruptive fissures south of Big Craters cinder cone
	Trench Mortar Flat (p)	Eruptive fissures between Big Cinder Butte and The Watchman cinder cone
	North Crater (p)	North Crater cinder cone
	Big Craters (Green Dragon) (p)	Eruptive fissure at north end of Big Craters cinder cone
	Kings Bowl (p)	Fissure vents north and south of Kings Bowl
	Wapi (p)	Vents at Pillar Butte
	Serrate (a-b)	North Crater (?)
B 3500 to 4500 yrs. b.p.	Devils Orchard (a-b)	North Crater cinder cone(?)
	Highway (a-b)	North Crater cinder cone(?) or tholoid vent(?) between Grassy Cone and Sunset Cone cinder cones
	Vermillion Chasm (p)	Eruptive fissures at Vermillion Chasm
	Deadhorse (p)	Eruptive fissures north and south of Black Top Butte cinder cone
	Devils Cauldron (p)	Devils Cauldron
	Minidoka (p)	Obscure vents located about 5 km northeast of New Butte cinder cone
	Larkspur Park (p)	Black Top Butte cinder cone (?)
	Rangeview (p)	Big Cinder Butte cinder cone(?)
C 5800 to 6200 yrs. b.p.	Indian Wells north (a)	Big Cinder Butte cinder cone(?)
	Indian Wells south (a)	Big Cinder Butte cinder cone(?)
	Sawtooth (a)	Big Cinder Butte cinder cone
	South Echo (p)	Eruptive fissures south of Echo Butte cinder cone
	Sheep Trail Butte (p-a)	Sheep Trail Butte cinder cone
	Fissure Butte (p-a)	Fissure Butte cinder cone
	Sentinel west (p)	The Sentinel cinder cone
	Sentinel south (p)	The Sentinel cinder cone
D About 6600 yrs. b.p.	Silent Cone (a)	Silent Cone cinder cone
	Carey Kipuka (a)	Silent Cone cinder cone (?)
	Little Park (a)	Silent Cone cinder cone (?)
	Little Laidlaw Park (a)	Silent Cone cinder cone (?)
E 7300 to 7900 yrs. b.p.	Grassy Cone (p)	Grassy Cone cinder cone
	Laidlaw Lake (p)	Grassy Cone cinder cone
	Lava Point (a)	Great Rift northwest of Echo Crater
F 10,000 to 11,000 yrs. b.p.	Fronghorn (p)	Great Rift near Sheep Trail Butte
	Bottleneck Lake (p)	Great Rift near Sheep Trail Butte
	Heifer Reservoir (p)	Great Rift near Crescent Butte
G 12,000 to 12,900 yrs. b.p.	Sunset (p)	Sunset Cone cinder cone
	Carey (p)	Sunset Cone cinder cone
	Lava Creek (p-a)	Vents near Lava Creek
H About 15,000 yrs. b.p.	Kimama (p)	unknown
	Bear Den Lake (p)	unknown
	Baseline (p)	unknown
	Little Prairie (p)	unknown
	Lost Kipuka (p)	unknown
	No Name (p)	unknown
* (p) (a) (a-b) (p-a)	Brown flow (p)	unknown
	chiefly pahoehoe flows	
	chiefly a'a flows	
	a'a and block flows	
	pahoehoe and a'a flows	
		Echo Crater and (or) Crescent Butte (?)