

Contrasting magma types and steady-state, volume-predictable, basaltic volcanism along the Great Rift, Idaho

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ABSTRACT

The Great Rift is an 85-km-long, 2- to 8-km-wide volcanic rift zone in the Snake River Plain, Idaho. Three latest Pleistocene to Holocene basaltic lava fields, Craters of the Moon, Kings Bowl, and Wapi, are located along the Great Rift. The Craters of the Moon lava field is a composite of more than 60 lava flows, 25 cinder cones, and at least 8 eruptive fissure systems. It covers 1,600 km² and contains ~30 km³ of lava flows and associated pyroclastic deposits. Field, radiocarbon, and paleomagnetic data show that the Craters of the Moon lava field formed in eight eruptive periods, each of which was typically several hundred years or less in duration and was separated from others before and after by intervals of several hundred to several thousand years. The first eruptive period began ~15,000 yr B.P., and the latest eruptive period ended ~2100 yr B.P. The small Kings Bowl lava field (3.3 km², 0.01 km³) and the larger Wapi lava field (330 km², 6 km³) both formed ~2250 yr B.P.

Three magma types have fed flows along the Great Rift. The types are (1) a contaminated type that has a SiO₂ range of ~49%–64% and commonly shows petrographic evidence of contamination, (2) a fractionated type that has a SiO₂ range of ~44%–54% and shows no evidence of contamination and whose chemical and mineralogical variation can be accounted for mainly by crystal fractionation, and (3) a Snake River Plain type that has a SiO₂ range of ~45%–48%, shows little evidence of fractionation, and is represented by Kings Bowl–Wapi flows and olivine basalts of the Snake River Plain. The contaminated and fractionated magma types were erupted at the Craters of the Moon lava field, and the Snake River Plain magma type was erupted at the Kings

Bowl and Wapi lava fields. These relations imply that the magma reservoirs are spatially isolated.

The magma output rate for the Craters of the Moon segment of the Great Rift was constant at ~1.5 km³/1,000 yr for the period from 15,000 to 7000 yr B.P. The rate increased to ~2.8 km³/1,000 yr from 7000 to 2000 yr B.P., mainly as a result of the addition of contaminated magma to the nearly constant output rate of fractionated magma. The Craters of the Moon segment of the Great Rift has experienced quasi-steady-state, volume-predictable volcanism for the last 15,000 yr. The recurrence interval of eruptive activity for the Craters of the Moon lava field ranges from several hundred to ~3,000 yr. Because the present interval has lasted ~2,100 yr, another eruptive period seems likely to occur within the next 1,000 yr. The steady-state, volume-predictable relationship suggests that 5–6 km³ of lava will be erupted in the next eruptive period.

INTRODUCTION

The central and eastern Snake River Plain of southern Idaho is a locus of young basaltic volcanism. Basaltic lava flows of the Snake River Plain were erupted from vents that are mostly confined to volcanic rift zones. These zones are narrow belts (typically 2–20 km wide) of faults, grabens, non-eruptive fissures, eruptive fissures, cinder-spatter cones, lava cones, and low shield volcanoes whose elongated vent craters lie above eruptive fissures (Wentworth and MacDonald, 1953; Kuntz, 1977a, 1977b). Most volcanic rift zones trend at right angles to the long axis of the plain, and many appear to be extensions of faults that bound basin-range mountains on the margins of the eastern Snake River Plain (Kuntz, 1977b).

The latest Pleistocene–Holocene Craters of

the Moon, Kings Bowl, and Wapi lava fields lie along the Great Rift, the most prominent volcanic rift zone in the Snake River Plain (Fig. 1). The purposes of this study were to determine the eruptive history, eruptive mechanisms, and magma petrogenesis for these lava fields and to evaluate volcanic hazards of the Great Rift area. In this report, we discuss radiocarbon ages, paleomagnetic data, major-element chemical analyses, and lava volumes for these three lava fields.

The entire Craters of the Moon lava field was mapped, and samples were collected for radiocarbon, paleomagnetic, and petrologic studies in 1978–1980. The eruptive history of the Craters of the Moon lava field has been discussed by Kuntz and others (1982, 1983) and is summarized in Table 1. The Kings Bowl lava field has been described by Covington (1977), King (1977), and Greeley and others (1977), and the Wapi lava field has been described by Champion (1973) and by Champion and Greeley (1977).

REGIONAL SETTING

The Snake River Plain is an arcuate topographic depression, 50 to 100 km wide, which extends for ~600 km across southern Idaho (Fig. 1). On the north, the plain cuts across Mesozoic to lower Tertiary plutonic rocks of the Idaho batholith and block-faulted mountains that consist of folded Paleozoic and Mesozoic rocks uplifted along northwest-trending normal faults during Cenozoic basin-and-range tectonism. The Snake River Plain is also bounded on the southeast side by basin-and-range, block-faulted mountains that were uplifted in the Cenozoic. Tertiary rhyolitic and basaltic rocks of the Owyhee Plateau border the southwest side of the plain. Upper Tertiary and Quaternary rhyolitic and basaltic rocks of the Yellowstone Plateau occur at the northeast end of the plain (Fig.

114°00'

113°30'

43°30'

43°15'

43°00'

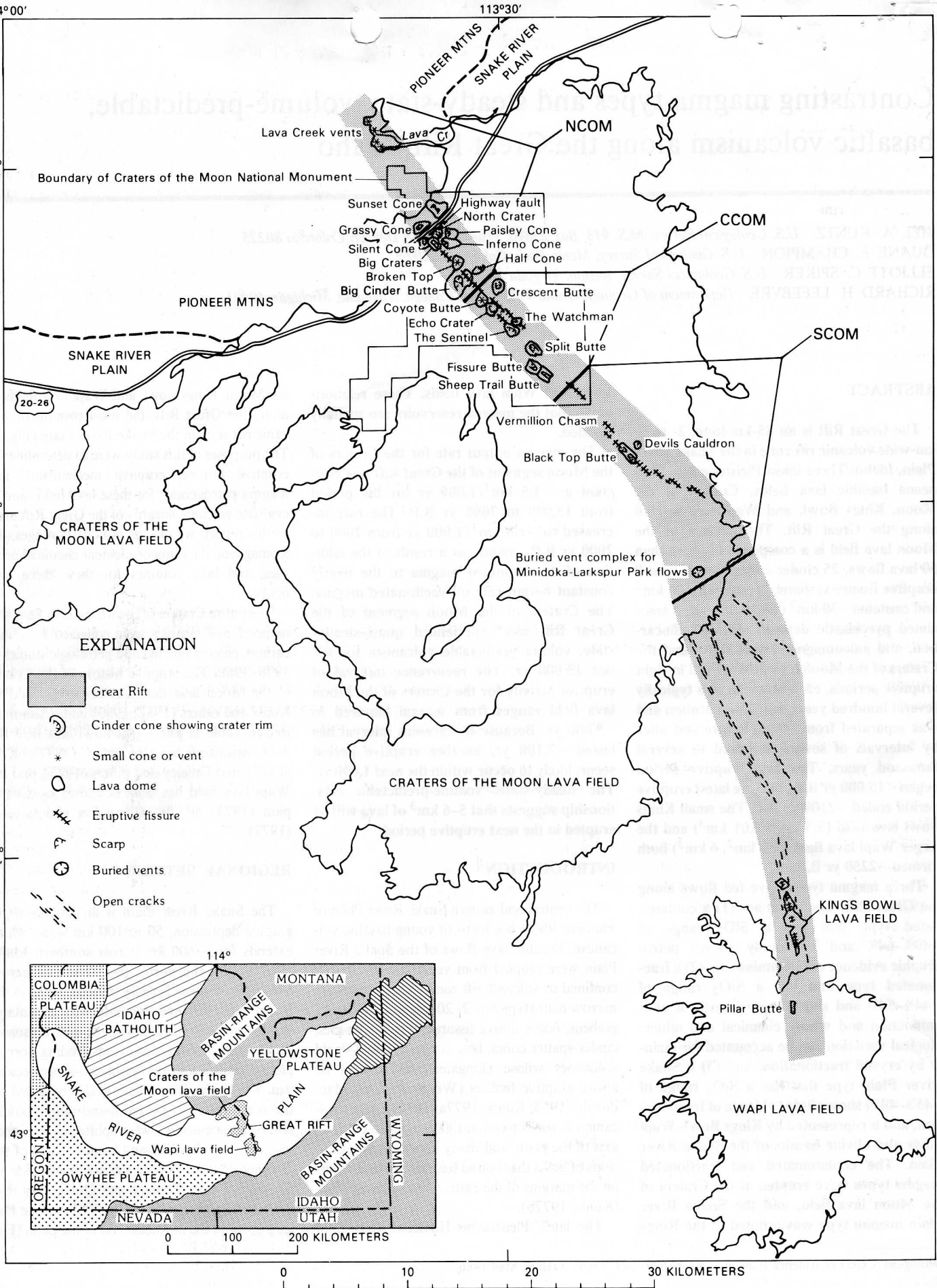


Figure 1. Map showing volcanic and structural features along the Great Rift and the Craters of the Moon, Kings Bowl, and Wapi lava fields (from Kuntz and others, 1982). Abbreviations NCOM, CCOM, and SCOM refer to northern, central, and southern segments, respectively, of the Craters of the Moon part of the Great Rift, as discussed in text. Inset is index map of southern Idaho showing generalized geology, latest Pleistocene-Holocene lava fields, and localities referred to in text.

1). The central and eastern parts of the Snake River Plain constitute a broad, flat, lava plain which consists, at the surface, of Pleistocene and Holocene basaltic lava flows and thin, discontinuous layers of interbedded loess, eolian sand, and alluvial fan deposits. The lava-sediment sequence has a total thickness of ~1 to 2 km near the area described in this report (Zohdy and Stanley, 1973; Stanley and others, 1977; Doherty and others, 1979).

The basaltic volcanism in the central and eastern Snake River Plain represents the latest stage of a complex tectonic and volcanic history characterized by an earlier stage of predominantly rhyolitic pyroclastic volcanism. Available data suggest that the rhyolitic rocks were erupted from a northeast-trending cluster of calderas that now mostly lie beneath the basaltic lava-sediment layer of the Snake River Plain (Armstrong and others, 1975; Eaton and others, 1975; Christiansen and McKee, 1978; Mabey and others, 1978). The earliest calderas formed ~15 m.y. ago near Twin Falls and were succeeded by progressively younger calderas northeastward to Yellowstone National Park.

THE GREAT RIFT AND ASSOCIATED VOLCANIC DEPOSITS

The Great Rift (Russell, 1902; Stearns, 1928; Murtaugh, 1961; Prinz, 1970; Kuntz and others, in press a) is an 85-km-long, 2- to 8-km-wide volcanic rift zone in the central Snake River Plain (Fig. 1). The Craters of the Moon lava field includes more than 60 lava flows and flow units, 25 cinder cones, and at least 8 eruptive fissure systems. The field covers an area of 1,600 km², contains >30 km³ of lava flows and pyroclastic deposits, and is the largest, predominantly Holocene lava field in the conterminous United States. Craters of the Moon flows were erupted during at least 8 eruptive episodes ~15,000 yr to ~2,100 yr ago (Table 1). The Great Rift emerges from beneath the southeastern limit of

the Craters of the Moon lava field as two paired sets of non-eruptive fissures that trend N27°W-N43°W (Fig. 1) and form the Open Crack rift segment of Prinz (1970).

The small Kings Bowl lava field (3.3 km², 0.01 km³) is the product of a single, relatively simple eruption along the southern part of the Great Rift (Greeley and others, 1977; King, 1977). It consists mainly of thin, shelly pahoehoe flows that formed during a fissure eruption which lasted probably several hours to several days (Kuntz and others, 1983).

The Wapi lava field (Champion, 1973; Champion and Greeley, 1977) is a low shield volcano (330 km², 6 km³). Our paleomagnetic data and analogues with well-studied Hawaiian eruptions (Swanson and others, 1979) suggest that the Wapi field probably formed in less than a few years. Radiocarbon and paleomagnetic data suggest that the Kings Bowl and Wapi lava fields formed simultaneously ~2,250 yr ago.

RADIOCARBON STUDIES

Forty-seven radiocarbon ages from twenty flows of the Craters of the Moon lava field were obtained for this study. Sampling methods, sample preparation techniques, and resulting ages are discussed more fully by Kuntz and others (in press b) and are described here only briefly. Radiocarbon ages of flows are summarized in Table 1.

Most samples were obtained by backhoe excavation beneath flows at sites along the margins of the lava field where tongues and lobes of lava moved across loess and eolian sand. A black, charred sediment layer, 1 to 10 cm thick, typically occurs beneath the flows and extends to within 0.2 to 1 m of their edges. The charred sediment contains dispersed, rounded grains, <0.1 mm, of charcoal and films of dark organic matter on sand, silt, and clay particles. The dark organic film is believed to represent soot from charred grass, sagebrush, roots, and humus that were partially combusted when overridden by lava.

As the organic-carbon content of the charred sediments is typically low (<2%) the samples were initially prepared by concentrating the carbon using a disaggregation-deflocculation method, which was followed by wet sieving and leaching with dilute HCl to remove traces of carbonate carbon. The radiocarbon ages for samples prepared in this way were significantly younger than expected, and some did not reflect known stratigraphic relations among flows. Radiocarbon ages for these samples, thus, probably reflect contamination by young carbon components.

A sample preparation technique that involves chemical digestion of younger carbon compo-

nents by hot alkali solution was devised in order to eliminate or significantly reduce contamination. The radiocarbon ages for charred sediment samples subjected to the hot alkali pretreatment are invariably older than those for paired samples pretreated only by disaggregation-deflocculation and acid leaching, and they generally reflect known stratigraphic relations among flows. A few ages were also determined for charcoal that was also pretreated using the hot alkali method. We conclude that the ages of the charred sediments and charcoal pretreated using the hot alkali method represent approximate and probably minimum ages for the overlying flows.

PALEOMAGNETIC STUDIES

Directions of remanent magnetization have been used to correlate and approximately date lava flows. Geomagnetic field changes that result from secular variation occur at a geologically rapid rate (~4°/century; Champion and Shoemaker, 1977) and thus permit assignment of lava flows to groups that have similar paleomagnetic directions. Conversely, dissimilar paleomagnetic directions indicate that two lava flows do not belong to the same group.

Methods used in the paleomagnetic studies largely followed established procedures (McElhinny, 1973), except that a suncompass was used exclusively for core orientation. Lava flows are generally sampled in cross section in paleomagnetic studies, but cross sections do not exist in Craters of the Moon flows because they are not eroded; thus, only the surfaces of these young flows were sampled. For this study, 1,282 cores were taken from 100 sites distributed among 41 flows. For the average sampling site, 12 independently oriented cores yield a 95% confidence circle of 2° or less about the mean (Fig. 2). At an average motion of the geomagnetic field of ~4°/century, this precision would permit recognition of 50-yr differences in time. Our knowledge of subtle tilting of flow surfaces, however, suggests that we probably cannot recognize angular differences that correspond to a time difference of less than a century.

ERUPTIVE PERIODS

Combined field, radiocarbon, and paleomagnetic data show that the Craters of the Moon lava field formed in at least eight distinct eruptive periods (Table 1). The criteria used to place lava flows in eruptive periods are (1) areal distribution, which includes eruption from vents along short (<10 km) segments of the Great Rift, (2) similar radiocarbon ages, and (3) similar remanent paleomagnetic field directions.

Paleomagnetic studies suggest that most of the

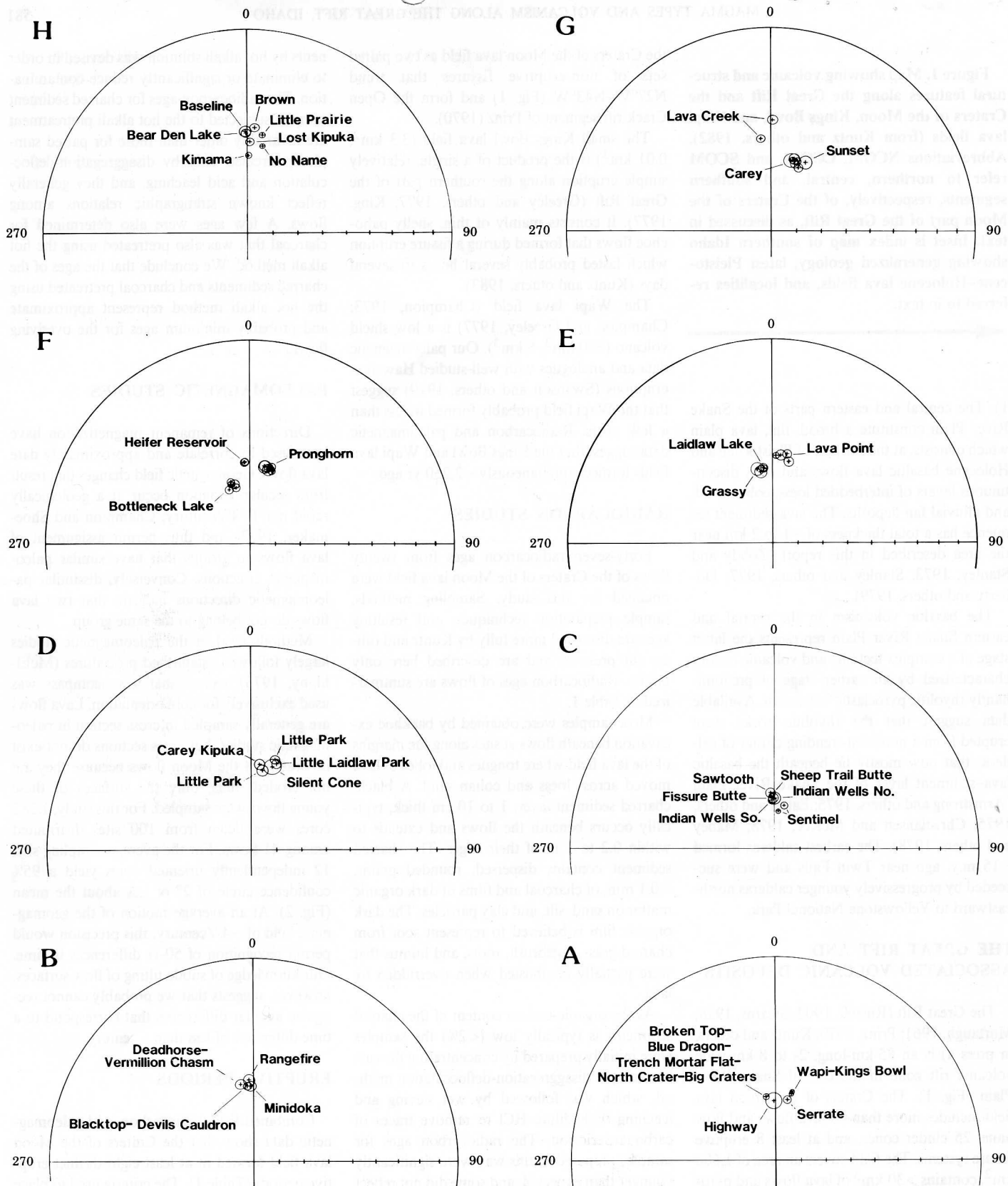


Figure 2. Equal-area diagrams of mean directions of remanent magnetization for lava flows and groups of lava flows for eruptive periods H through A for the Craters of the Moon, Kings Bowl, and Wapi lava fields, Idaho. Circles around mean directions represent 95% confidence estimates of mean-direction values.

TABLE 1. ERUPTIVE PERIODS, RADIOCARBON AGES, INFORMAL NAMES 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

Eruptive period	Radiocarbon age (yr), after Kuntz and others, (in press b)	Informal name and lava type of major flows*	Source vents (queried where uncertain)
A	n.d.	Broken Top (p)	Eruptive fissures, east and south flanks of Broken Top cinder cone
	2,076 $\pm$ 45	Blue Dragon (p)	Eruptive fissures south of Big Craters cinder cone complex
	2,205 $\pm$ 25	Trench Mortar Flat (p)	Eruptive fissures between Big Cinder Butte and The Watchman cinder cones
	n.d.	North Crater (p)	North Crater cinder cone
	2,400 $\pm$ 300	Big Craters (Green Dragon) (p)	Eruptive fissure at north end of Big Craters cinder cone
	n.d.	Serrate (a-b)	North Crater cinder cone (?)
	n.d.	Devils Orchard (a-b)	North Crater cinder cone (?)
	n.d.	Highway (a-b)	North Crater cinder cone (?) or tholoid vent (?) between Grassy Cone and Sunset Cone cinder cones
B	2,222 $\pm$ 100	Kings Bowl (p)	Fissure vents north and south of Kings Bowl
	2,270 $\pm$ 50	Wapi (p)	Vents at Pillar Butte
	n.d.	Vermillion Chasm (p)	Eruptive fissures at Vermillion Chasm
	4,300 $\pm$ 60	Deadhorse (p)	Eruptive fissures north and south of Black Top Butte cinder cone
	3,660 $\pm$ 60	Devils Cauldron (p)	Devils Cauldron
	3,590 $\pm$ 70	Minidoka (p)	Obscure vents about 5 km northeast of New Butte cinder cone
	n.d.	Larkspur Park (p)	Blacktop Butte cinder cone (?)
	4,510 $\pm$ 100	Rangefire (p)	Blacktop Butte cinder cone
C	n.d.	Blacktop (p)	Blacktop Butte cinder cone
	n.d.	Indian Wells North (a)	Big Cinder Butte cinder cone (?)
	n.d.	Indian Wells South (a)	Big Cinder Butte cinder cone (?)
	6,020 $\pm$ 60	Sawtooth (a)	Big Cinder Butte cinder cone
	n.d.	South Echo (p)	Eruptive fissures south of Echo Butte cinder cone
	n.d.	Sheep Trail Butte (p-a)	Sheep Trail Butte cinder cone
	n.d.	Fissure Butte (p-a)	Fissure Butte cinder cone
	n.d.	Sentinel (p)	The Sentinel cinder cone
D	n.d.	Silent Cone (a)	Silent Cone cinder cone
	6,600 $\pm$ 60	Carey Kipuka (a)	Silent Cone cinder cone (?)
	6,500 $\pm$ 60	Little Park (a)	Silent Cone cinder cone (?)
	n.d.	Little Laidlaw Park (a)	Silent Cone cinder cone (?)
E	7,360 $\pm$ 60	Grassy Cone (p)	Grassy Cone cinder cone
	7,470 $\pm$ 80	Laidlaw Lake (p)	Grassy Cone cinder cone
	7,840 $\pm$ 140	Lava Point (a)	Great Rift northwest of Echo Crater cinder cone (?)
F	10,240 $\pm$ 120	Pronghorn (p)	Great Rift near Sheep Trail Butte cinder cone
	10,670 $\pm$ 150	Heifer Reservoir (p)	Great Rift near Crescent Butte cinder cone
	11,000 $\pm$ 100	Bottleneck Lake (p)	Great Rift near Sheep Trail Butte cinder cone
G	12,010 $\pm$ 150	Sunset (p)	Sunset Cone cinder cone
	(12,000)	Carey (p)	Sunset Cone cinder cone
	12,760 $\pm$ 150	Lava Creek (p-a)	Vents near Lava Creek
H	15,100 $\pm$ 160	Kimama (p)	unknown unknown unknown unknown unknown unknown unknown } Echo Crater and (or) Crescent Butte cinder cones
	n.d.	Bear Den Lake (p)	
	n.d.	Baseline (p)	
	n.d.	Little Prairie (p)	
	n.d.	Lost Kipuka (p)	
	n.d.	No Name (p)	
	n.d.	Brown flow (p)	

(n.d.) not determined.

* (p) chiefly pahoehoe flows.

(a) chiefly a'a flows.

(a-b) a'a and block flows.

(p-a) pahoehoe and a'a flows.

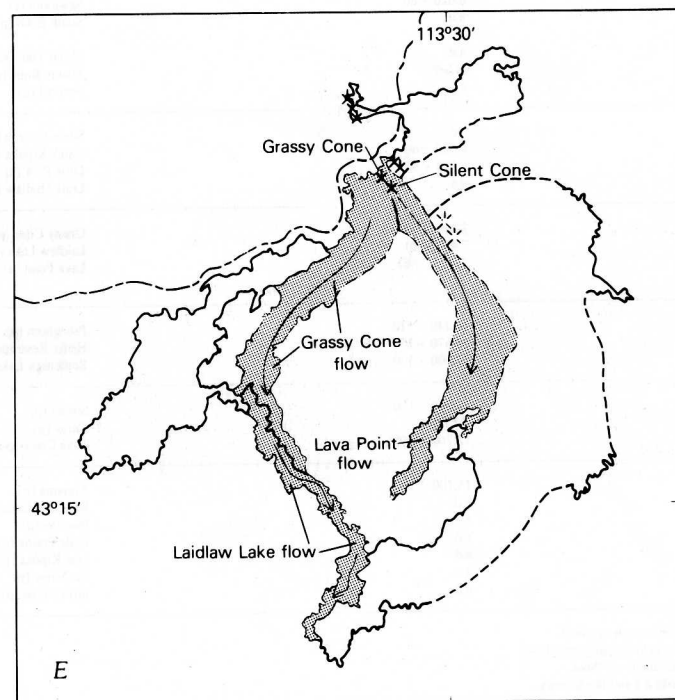
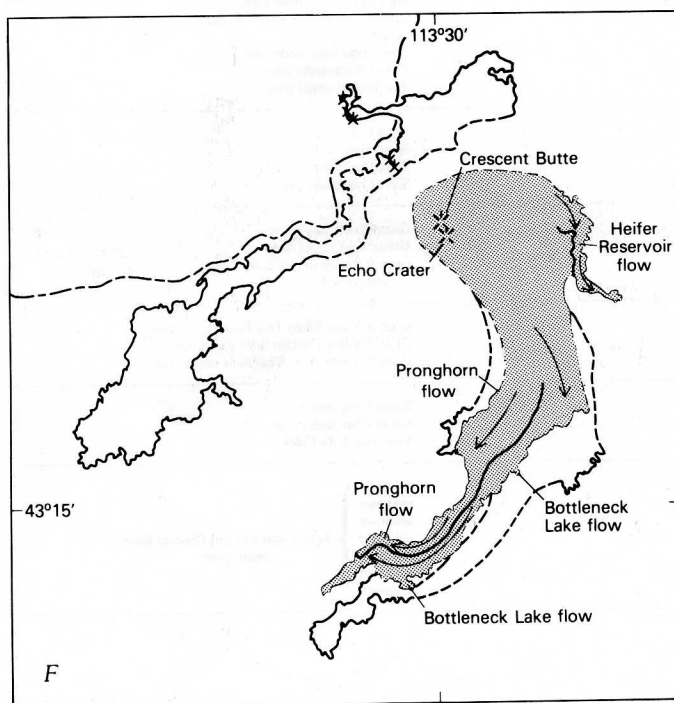
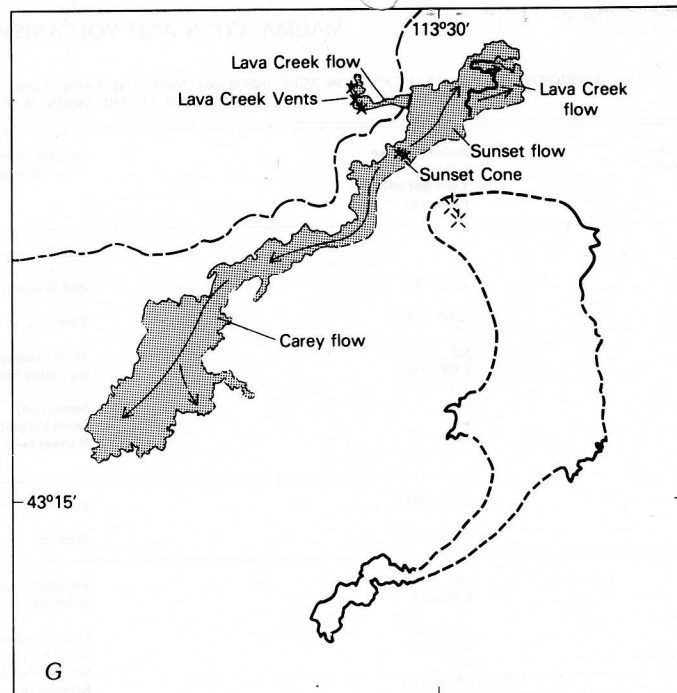
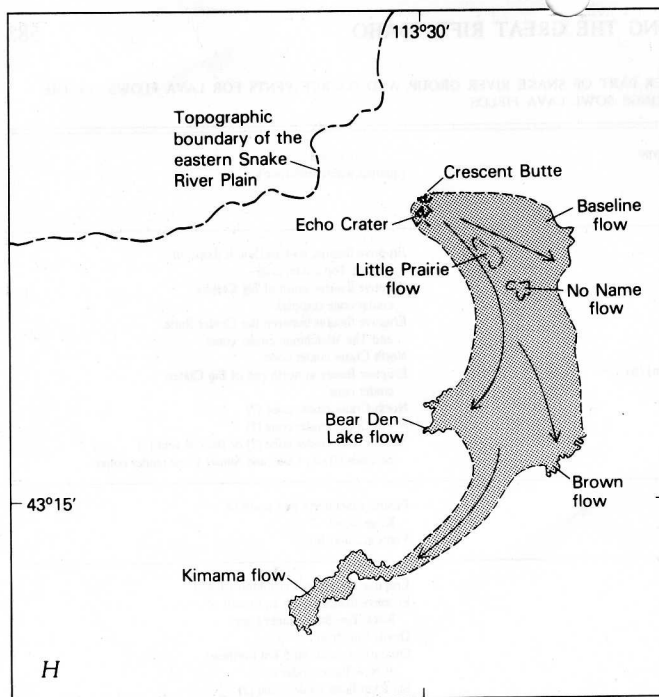
younger eruptive periods lasted <100 yr. For eruptive periods for which several radiocarbon ages span more than a few hundred years, the ages are believed to reflect various degrees of contamination and to suggest a greater span of time than that which actually exists. Alternatively, the eruptive periods may be several hundred years long and consist of several dis-

crete volcanic episodes. The intervals between eruptive periods may have been times of volcanic quiescence or sporadic activity, and the time within eruptive periods probably involved irregular eruptive activity. These factors cannot be specified more precisely at the present time because many critical flows have not been dated and our methods of dating lack sufficient preci-

sion. Details of volcanic events in each eruptive period are discussed by Kuntz and others (1982) and are summarized in Figure 3.

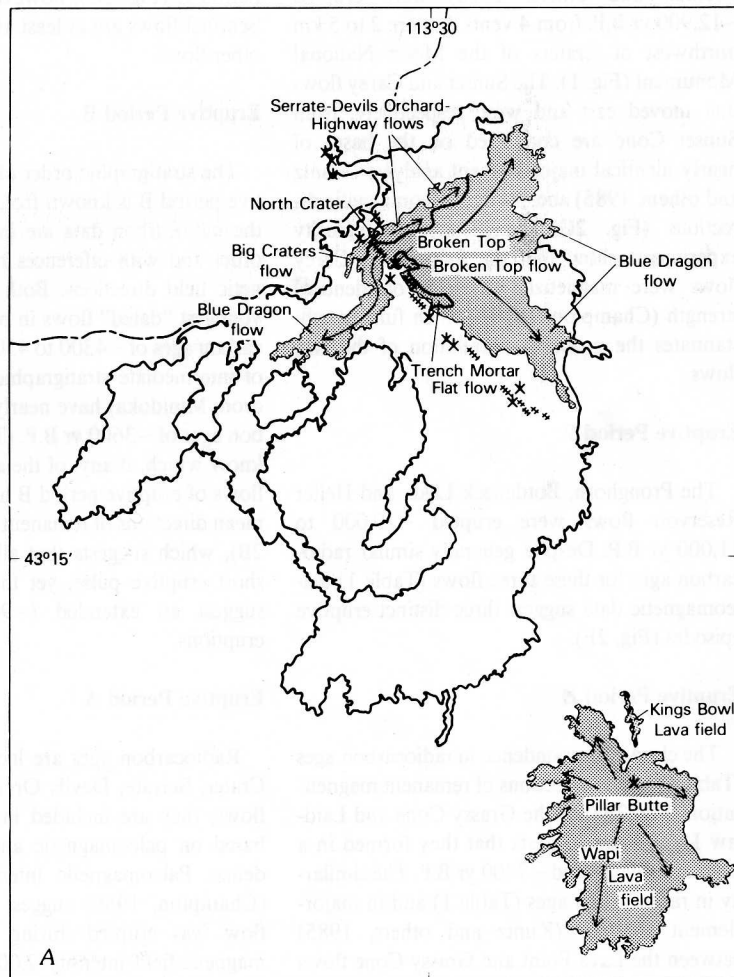
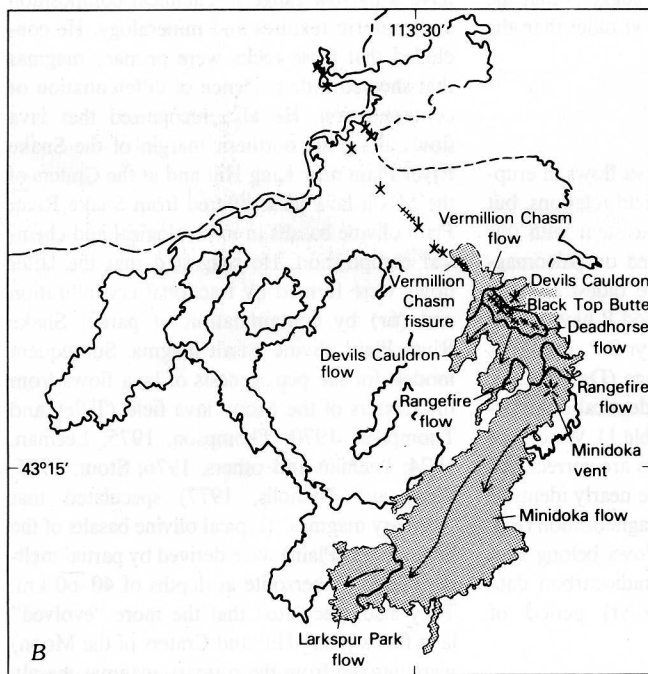
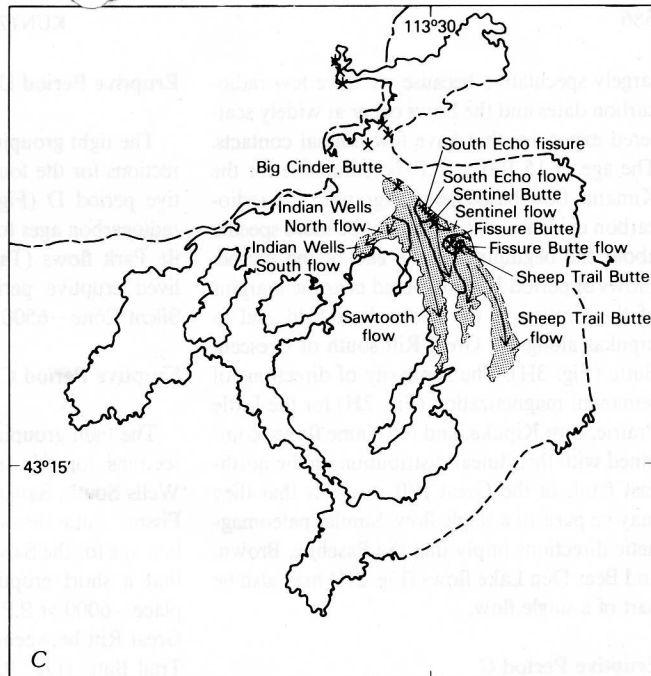
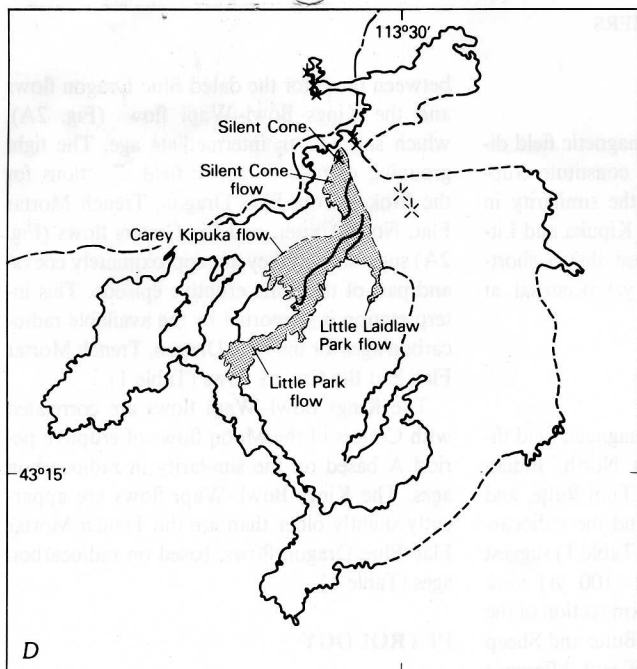
Eruptive Period H

The absolute age and stratigraphic order of the flows in eruptive period H (Table 1) are



0 50 KILOMETERS

Figure 3. Evolution of the Craters of the Moon lava field in eight eruptive periods from H, the oldest, through A, the youngest (from Kuntz and others, 1982).



0 KILOMETERS 50

Figure 3. (Continued).

largely speculative because we have few radiocarbon dates and the flows occur at widely scattered exposures that have few mutual contacts. The age of 15,100 yr B.P. is reasonable for the Kimama flow based on stratigraphic and radiocarbon evidence, but we cannot be more specific about the beginning or the end of the period. Flows of period H are exposed near the margins of the Craters of the Moon lava field and in kipukas along the Great Rift south of Crescent Butte (Fig. 3H). The similarity of directions of remanent magnetization (Fig. 2H) for the Little Prairie, Lost Kipuka, and No Name flows, combined with their linear distribution on the northeast flank of the Great Rift, suggests that they may be parts of a single flow. Similar paleomagnetic directions imply that the Baseline, Brown, and Bear Den Lake flows (Fig. 2H) may also be part of a single flow.

Eruptive Period G

The Lava Creek flows (Anderson, 1929; Leeman and others, 1976) were erupted ~12,900 yr B.P. from 4 vents that are 2 to 5 km northwest of Craters of the Moon National Monument (Fig. 1). The Sunset and Carey flows that moved east and west, respectively, from Sunset Cone are correlated on the bases of nearly identical major-element analyses (Kuntz and others, 1985) and similar paleomagnetic directions (Fig. 2G). Magnetic paleointensity experiments show that the Sunset and Carey flows were magnetized in fields of identical strength (Champion, 1980), which further substantiates the probable correlation of the two flows.

Eruptive Period F

The Pronghorn, Bottleneck Lake, and Heifer Reservoir flows were erupted ~10,000 to 11,000 yr B.P. Despite generally similar radiocarbon ages for these three flows (Table 1), paleomagnetic data suggest three distinct eruptive episodes (Fig. 2F).

Eruptive Period E

The close correspondence in radiocarbon ages (Table 1) and in directions of remanent magnetization (Fig. 2E) for the Grassy Cone and Laidlaw Lake flows suggests that they formed in a short eruptive period ~7400 yr B.P. The similarity in radiocarbon ages (Table 1) and in major-element analyses (Kuntz and others, 1985) between the Lava Point and Grassy Cone flows suggests that the Lava Point flow belongs in eruptive period E.

Eruptive Period D

The tight grouping of paleomagnetic field directions for the four flows that constitute eruptive period D (Fig. 2D) and the similarity in radiocarbon ages for the Carey Kipuka and Little Park flows (Table 1) suggest that a short-lived eruptive period (<100 yr) occurred at Silent Cone ~6500 yr B.P.

Eruptive Period C

The tight grouping of paleomagnetic field directions for the Indian Wells North, Indian Wells South, Sawtooth, Sheep Trail Butte, and Fissure Butte flows (Fig. 2C) and the radiocarbon age for the Sawtooth flow (Table 1) suggest that a short eruptive period (<100 yr) took place ~6000 yr B.P. from a 10-km section of the Great Rift between Big Cinder Butte and Sheep Trail Butte (Fig. 3C). The significant difference in direction of remanent magnetization between the Sentinel flows and other flows in eruptive period C (Fig. 2C), however, suggests that the Sentinel flows are at least 100 yr older than the other flows.

Eruptive Period B

The stratigraphic order of lava flows in eruptive period B is known from field relations, but the radiocarbon data are inconsistent with this order and with inferences based on paleomagnetic field directions. Both the oldest and the youngest "dated" flows in period B have radiocarbon ages of ~4300 to 4500 yr B.P., but flows of intermediate stratigraphic age (Devils Cauldron, Minidoka) have nearly identical radiocarbon ages of ~3600 yr B.P. (Table 1). We do not know which, if any, of the ages are correct. All flows of eruptive period B have nearly identical mean directions of remanent magnetization (Fig. 2B), which suggests that all flows belong to a short eruptive pulse, yet the radiocarbon data suggest an extended (~900 yr) period of eruptions.

Eruptive Period A

Radiocarbon ages are lacking for the North Crater, Serrate, Devils Orchard, and Highway flows; they are included in eruptive period A based on paleomagnetic and stratigraphic evidence. Paleomagnetic intensity measurements (Champion, 1980) suggest that the Highway flow was erupted during a peak of global magnetic-field intensity 2,000 to 2,500 yr ago. In addition, the directions of remanent magnetization for the Highway and Serrate flows fall

between those for the dated Blue Dragon flows and the Kings Bowl–Wapi flows (Fig. 2A), which suggests an intermediate age. The tight grouping of paleomagnetic field directions for the Broken Top, Blue Dragon, Trench Mortar Flat, North Crater, and Big Craters flows (Fig. 2A) suggests that they are approximately coeval and part of the same eruptive episode. This interpretation is supported by the available radiocarbon ages for the Blue Dragon, Trench Mortar Flat, and Big Craters flows (Table 1).

The Kings Bowl–Wapi flows are correlated with Craters of the Moon flows of eruptive period A based on the similarity in radiocarbon ages. The Kings Bowl–Wapi flows are apparently slightly older than are the Trench Mortar Flat–Blue Dragon flows, based on radiocarbon ages (Table 1).

PETROLOGY

Stone's (1967, 1970) studies of basaltic lava flows of the Snake River Plain showed that they have a narrow range in chemical composition and uniform textures and mineralogy. He concluded that these rocks were primary magmas that showed little evidence of differentiation or contamination. He also recognized that lava flows along the northern margin of the Snake River Plain near King Hill and at the Craters of the Moon lava field differed from Snake River Plain olivine basalts in mineralogical and chemical composition. He suggested that the latter flows were formed by fractional crystallization and (or) by contamination of parent Snake River Plain olivine basalt magma. Subsequent models for the petrogenesis of lava flows from the Craters of the Moon lava field (Tilley and Thompson, 1970; Thompson, 1975; Leeman, 1974; Leeman and others, 1976; Stout, 1975; Stout and Nicholls, 1977) speculated that "primary magmas" (typical olivine basalts of the Snake River Plain) were derived by partial melting of spinel ilmenite at depths of 40–60 km. They also speculated that the more "evolved" lava flows (King Hill and Craters of the Moon) were derived from the primary magmas mainly by crystal fractionation of observed phenocryst phases at pressures of ~8–10 kbar (which correspond to depths of ~30 km) and, possibly, by various types and amounts of contamination of primitive magma.

Petrography and Chemistry of Lava Flows of the Snake River Plain

Snake River Plain Olivine Basalts. The modal composition of typical Snake River Plain basalts, determined by Stone (1967) from opti-

cal data, is olivine (Fo₈₀₋₅₀), a single clinopyroxene (augite to ferroaugite), plagioclase (An₇₀₋₅₀), titanomagnetite, ilmenite, and brown glass. The rocks typically are coarse grained, most crystals are 0.5 to 3 mm long, and textures range from ophitic and subophitic to intergranular and diktytaxitic. Inequigranular basalts consist typically of 0.5- to 2-mm euhedral and subhedral olivine crystals and a diktytaxitic, subophitic matrix of olivine, plagioclase, clinopyroxene, and opaque crystals <0.2 mm long.

Snake River Plain basalts are chemically distinctive if compared to most other basalts; they are low in SiO₂ and total alkalis and relatively high in total iron (Stone, 1967, 1970). Most contain normative olivine and hypersthene and are olivine tholeiites in the classification of Yoder and Tilley (1962). Some are alkali olivine basalts based on mineralogical and thermodynamic classifications (Stout, 1975; Stout and Nicholls, 1977).

King Hill Lava Flows. The King Hill lava flows contain as much as 64% SiO₂ and consist of olivine (Fo₆₀₋₂₄), plagioclase (An₅₆₋₂₅), clinopyroxene (subcalcic augite), apatite, and opaque minerals (Stone, 1967). Stone noted that King Hill flows have disequilibrium textures (resorption of plagioclase, clinopyroxene, and anorthoclase) and contain disequilibrium minerals (anorthoclase, hypersthene). He recognized the chemical and mineralogical similarity of the King Hill and Craters of the Moon lava flows.

Flows of the Craters of the Moon Lava Field. Lava flows of the Craters of the Moon lava field are distinctly different, both texturally and modally, from Snake River Plain basalts. Craters of the Moon flows also have a broad range in chemical composition (Kuntz and others, 1985). Most Craters of the Moon flows that contain less than ~51% SiO₂ are hypocrystalline, partly diktytaxitic, and porphyritic and have 0.1- to 1-mm phenocrysts of olivine (Fo₇₀₋₅₀) and plagioclase (An₆₀₋₄₀). The larger crystals are in an intergranular to subophitic matrix of olivine; plagioclase; blades and irregular patches of brown clinopyroxene (augite-ferroaugite); an equant, partly skeletal, opaque mineral (probably titanomagnetite); a feathery, bladed opaque mineral (probably ilmenite); and brown glass. All of the matrix crystals are typically <0.5 mm long.

Most Craters of the Moon flows that contain more than ~51% SiO₂ are hypocrystalline and fine grained (most crystals <0.5 mm long), and they contain microphenocrysts of olivine (Fo₅₀₋₂₅) and plagioclase (An₄₀₋₂₀). The larger crystals are in a matrix of <0.1-mm plagioclase, olivine, and subophitic brown clinopyroxene crystals; equant opaque minerals; and brown

glass. Petrographic evidence for contamination in some, but not all, of these flows includes disequilibrium mineral assemblages and textures. Xenoliths of granulite and gneissic rocks are common in the silica-rich flows (Leeman, 1980); less common are clots of siliceous pumice. Most of these rocks also contain xenocrysts of corroded anorthoclase, resorbed plagioclase (An₄₀₋₂₀), rounded green clinopyroxene, olivine (Fo₂₅₋₁₀), apatite, magnetite, and zircon in addition to xenolithic aggregates of some or all of these minerals.

Contamination of some Craters of the Moon flows may have occurred by several mechanisms, either singly or in combination; these include (1) partial or complete fusion of gneissic-granulitic xenoliths, as suggested by clinopyroxene, olivine, zircon, and plagioclase xenocrysts, (2) mixing of basaltic and silicic magmas, the latter containing phenocrysts of anorthoclase, magnetite, apatite, and plagioclase, and (3) mixing of basaltic magma with partial melt extracted from wall rocks of magma reservoirs. Xenoliths of partly fused dacitic to rhyolitic rocks, derived from the nearby, near-surface, Eocene Challis Volcanics(?), occur in a few Craters of the Moon flows that contain <51% SiO₂, such as the Lava Creek flows, but there is no petrographic or chemical evidence that these inclusions have been digested and incorporated into Craters of the Moon basaltic rocks.

Flows of the Kings Bowl and Wapi Lava Fields. Lava flows of these lava fields are texturally and mineralogically similar to typical Snake River Plain olivine basalts. The Kings Bowl and Wapi flows are mainly holocrystal-

line, diktytaxitic, and coarse grained, and most crystals are 0.5 to 2.0 mm in longest dimension. The largest crystals are olivine (Fo₈₀₋₆₀) and plagioclase (~An₆₀). The matrix consists of plagioclase, olivine, intergranular to subophitic brown clinopyroxene, and a feathery opaque mineral, all of which are 0.1 to 0.5 mm long. The Kings Bowl and Wapi flows have chemical characteristics that are more akin to those of Snake River Plain basalts than to those of even the most silica-poor Craters of the Moon flows (Kuntz and others, 1985).

Major-Element Analyses

One hundred sixty-six major-element analyses are available for lava flows from the Craters of the Moon, Kings Bowl, and Wapi lava fields (Kuntz and others, 1985). These analyses reflect the broad changes in lava composition within and between eruptive periods and are used to define magma types.

Craters of the Moon lava flows range in composition from iron-, alkali-, and phosphorus-rich basalts to latites in the terminology of Cox and others (1979). They are alkaline in the terminology of Irvine and Baragar (1971) and of Macdonald and Katsura (1964) and have a total silica range from 44.4% to 63.8% (Fig. 4). Even the Craters of the Moon flows that have the lowest SiO₂ content differ from average Snake River Plain basalts in that they have more TiO₂, total iron, Na₂O, K₂O, and P₂O₅ and less MgO and CaO.

The Wapi and Kings Bowl lava flows have the highest contents of MgO and CaO and the lowest contents of K₂O and Na₂O of all of the

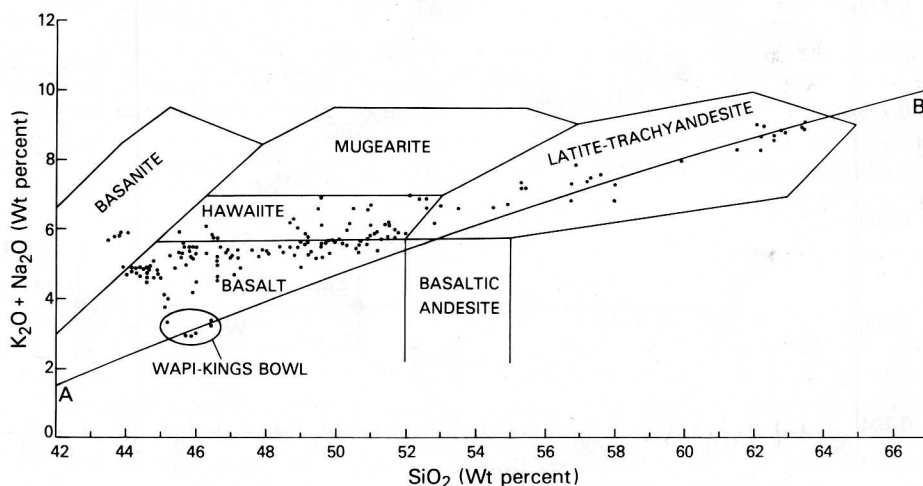


Figure 4. Na₂O + K₂O versus SiO₂ plot for analyzed rocks from Craters of the Moon, Wapi, and Kings Bowl lava fields. Line A-B separates alkaline from subalkaline fields (Irvine and Baragar, 1971). Nomenclature from Cox and others (1979).

Holocene-upper Pleistocene flows along the Great Rift. The Kings Bowl and Wapi lava flows clearly represent eruptions from a magma source that was not physically connected to the sources that fed Craters of the Moon flows.

Rb/Sr Data

Contamination of high-silica, Craters of the Moon lava flows by incorporation of xenocrysts and xenoliths, and possibly by partial melt derived from deep-crustal rocks, into low-silica ba-

saltic magma is supported by the Rb-Sr data of Leeman (1974) and Leeman and Manton (1971), which are summarized in Figure 5. The positive covariation between $\text{Sr}^{87}/\text{Sr}^{86}$ and Rb/Sr, between $\text{Sr}^{87}/\text{Sr}^{86}$ and SiO_2 , and between $\text{Sr}^{87}/\text{Sr}^{86}$ and Rb and the negative covariation between $\text{Sr}^{87}/\text{Sr}^{86}$ and Sr suggest variable contamination of more primitive Craters of the Moon magmas by more radiogenic crustal rocks. Craters of the Moon rocks that have higher SiO_2 contents have more-variable and higher $\text{Sr}^{87}/\text{Sr}^{86}$ ratios and are probably more

contaminated than are other Craters of the Moon rocks that have lower SiO_2 contents. The Rb-Sr data also suggest that the Kings Bowl and Wapi lava flows have not been affected by contamination.

Magma Types for Lava Flows along the Great Rift

A continuum exists in petrographic characteristics and major-element chemistry for flows erupted along the Great Rift. For purposes of

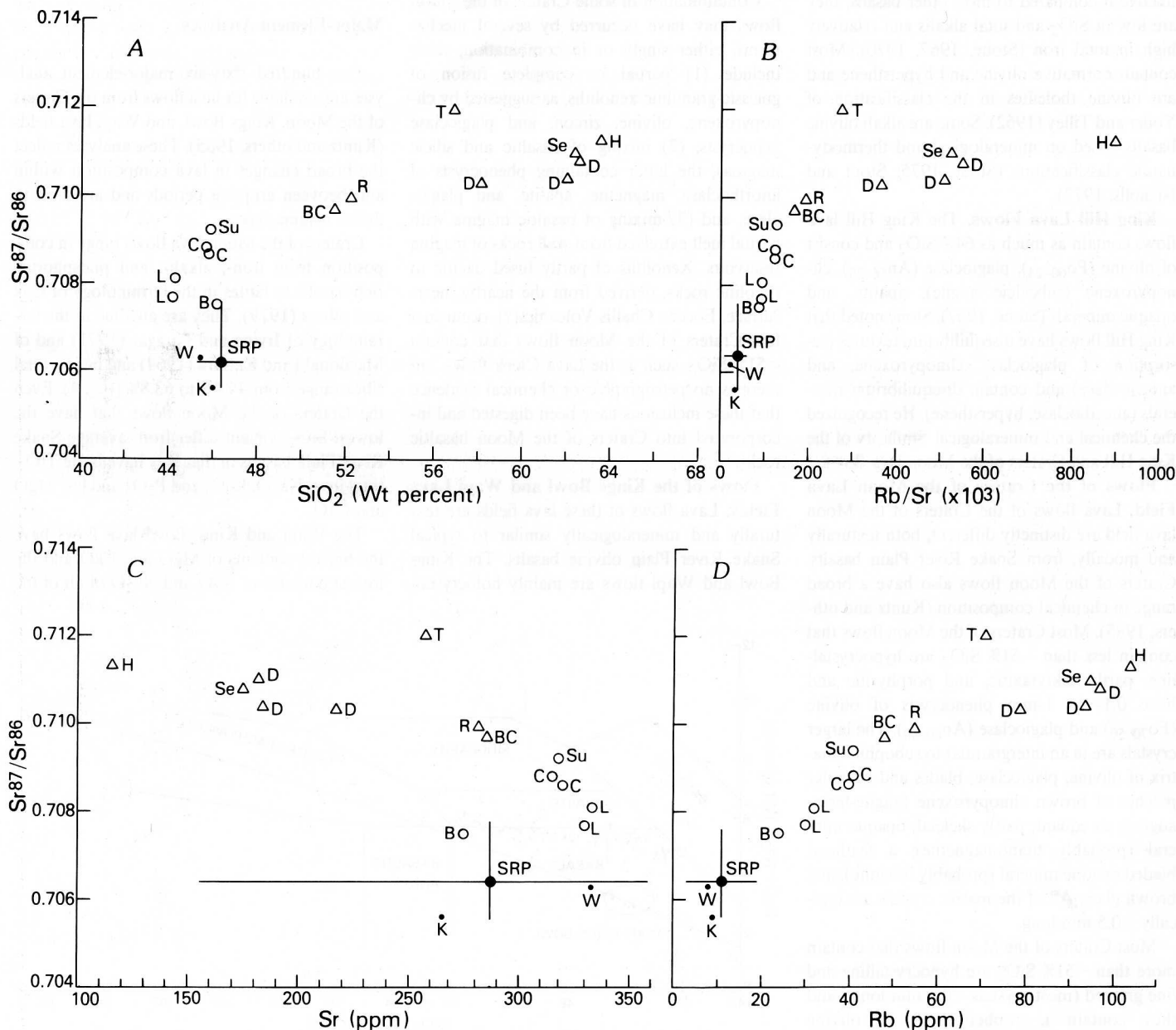


Figure 5. Plot of (A) $\text{Sr}^{87}/\text{Sr}^{86}$ versus SiO_2 , (B) $\text{Sr}^{87}/\text{Sr}^{86}$ versus Rb/Sr, (C) $\text{Sr}^{87}/\text{Sr}^{86}$ versus Sr, and (D) $\text{Sr}^{87}/\text{Sr}^{86}$ versus Rb for rocks of the Craters of the Moon, Kings Bowl, and Wapi lava fields. Also shown are data for average olivine tholeiites of Snake River Plain (abbreviated SRP, symbol with error bars). Data from Leeman (1974), Leeman and Manton (1971), and Kuntz and others (1985).

EXPLANATION

- | | | |
|-------------------------|----------------|----------------------|
| • SRP type flows | B Brown Flow | R Rangefire |
| △ Contaminated flows | L Lava Creek | T Trench Mortar Flat |
| ○ Noncontaminated flows | C Carey | D Devils Orchard |
| W Wapi | Su Sunset | Se Serrate |
| K Kings Bowl | BC Big Craters | H Highway |

calculation of volume of lava flows of different magma types, however, we arbitrarily define three subdivisions of the continuum. These subdivisions include (1) a *contaminated type*, represented by Craters of the Moon flows, which has a SiO_2 range of 49%–64% and which commonly contains xenoliths of granulites and gneisses and xenocrysts of disequilibrium minerals, thereby accounting for chemical and mineralogical variation mainly by contamination of basaltic magma by more siliceous rocks or melts; (2) a *fractionated type*, represented by Craters of the Moon flows, has a SiO_2 range of 44%–54%, lacks disequilibrium minerals and textures, and the chemical and mineralogical variation of which can be accounted for mainly by crystal fractionation; and (3) a *Snake River Plain type*,

represented by the Kings Bowl and Wapi flows, which strongly resembles the Snake River Plain olivine basalts in mineralogy, texture, and major-element chemistry and shows little evidence of fractionation. Craters of the Moon flows that have SiO_2 contents of 49%–51% and that lack petrographic evidence for contamination, but are spatially and temporally associated with flows that show petrographic evidence of contamination, are also assigned to the contaminated magma type. The latter group of flows (Little Park and Carey Kipuka flows, eruptive period D) may have completely dissolved xenocrysts and xenoliths, mixed with holohyaline partial melt, or, more likely, thin sections of these flows fail to reveal xenoliths, xenocrysts, or pumiceous clots that are, in fact, present.

MAJOR-ELEMENT VARIATION IN CRATERS OF THE MOON LAVA FLOWS

The changes in SiO_2 content of Craters of the Moon lava flows with time (Fig. 6) illustrate that (1) the chemical diversity of Craters of the Moon lava flows increases with time; (2) there is a general trend from older, more primitive lava flows in the earlier eruptive periods to younger, more evolved lava flows in later eruptive periods; (3) some flows in all eruptive periods have SiO_2 contents of <47%; and (4) most eruptive periods are characterized by early, lower silica lava flows followed by successively younger, higher silica flows.

The increasing chemical diversity of Craters

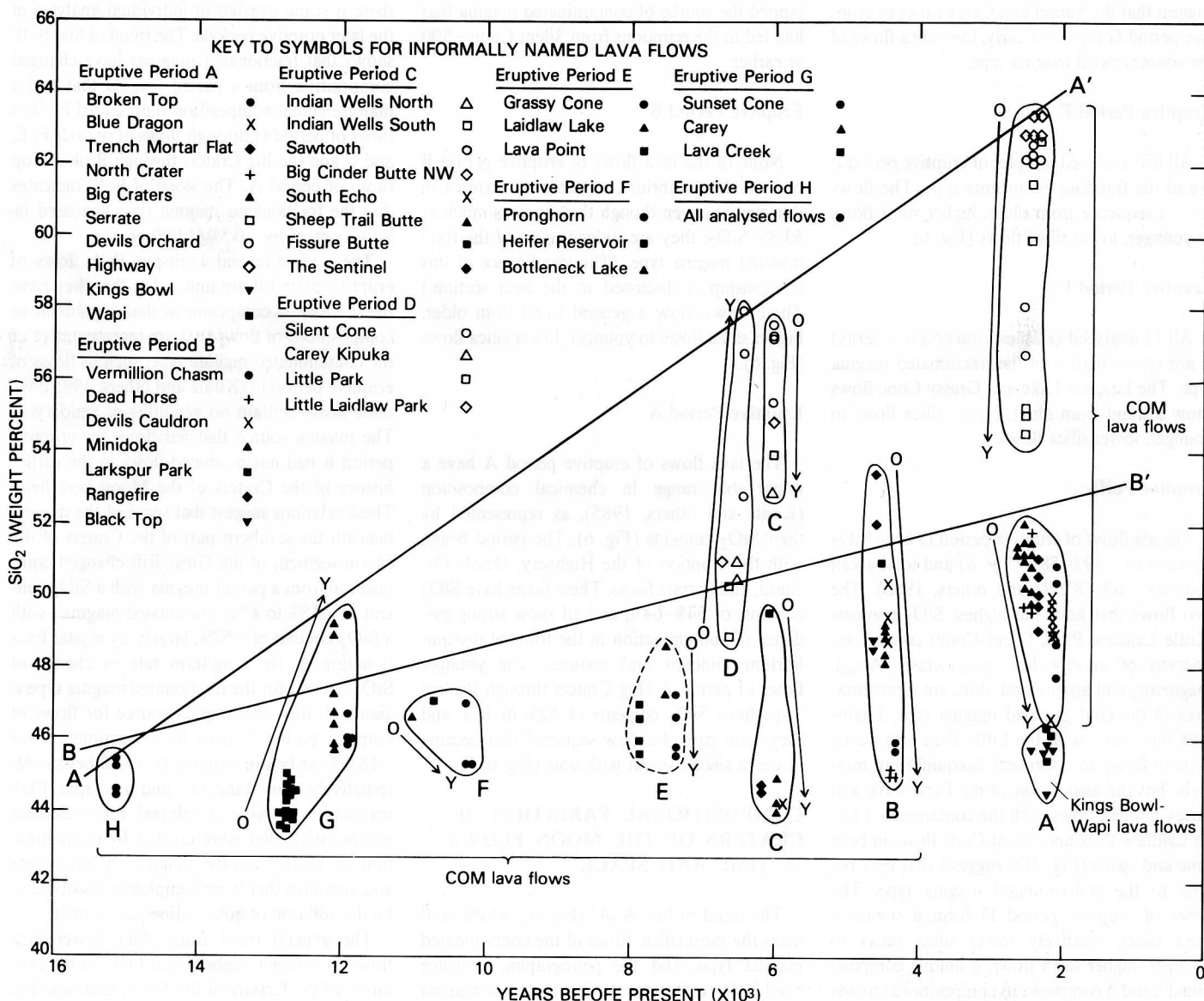


Figure 6. Weight percent SiO_2 versus age of lava flows for analyzed rocks of the Craters of the Moon (abbreviated COM), Kings Bowl, and Wapi lava fields. If data warrant such an interpretation, compositional trends in eruptive periods are shown by arrows. Y and O refer to younger and older flows within an eruptive period. Lines A–A' and B–B' are discussed in text. For Craters of the Moon flows, open symbols are for contaminated rocks, and solid symbols are for fractionated rocks.

of the Moon lava flows with time is chiefly a result of the effect of eruption of increasingly more fractionated and more contaminated lava flows and implies a progressive change in the composition of magma source(s) by continued fractionation and (or) assimilation of greater amounts of deep-crustal rocks. The general trend from older, higher silica flows to younger, lower silica flows within most eruptive periods suggests that the magma bodies are chemically zoned in a vertical sense and are emptied from top to bottom.

Eruptive Periods H and G

All lava flows of eruptive periods H and G are representative of the fractionated magma type, but relationships discussed in the next section suggest that the Sunset and Carey flows of eruptive period G represent early, low-silica flows of the contaminated magma type.

Eruptive Period F

All five analyzed samples of eruptive period F are of the fractionated magma type. The flows form a sequence from older, higher silica flows to younger, lower silica flows (Fig. 6).

Eruptive Period E

All 11 analyzed samples from eruptive period E are representative of the fractionated magma type. The Laidlaw Lake and Grassy Cone flows show a trend from older, higher silica flows to younger, lower silica flows.

Eruptive Period D

The a'a flows of eruptive period D have SiO₂ contents of ~49%–58% (Fig. 6) and total alkali contents >6% (Kuntz and others, 1985). The two flows that have the highest SiO₂ contents (Little Laidlaw Park, Silent Cone) contain xenocrysts of anorthoclase, plagioclase (An₃₀), magnetite, and apatite and, thus, are representatives of the contaminated magma type. Examined thin sections of the Little Park and Carey Kipuka flows do not reveal disequilibrium minerals, but the association of the Little Park and Carey Kipuka flows with the contaminated Little Laidlaw Park and Silent Cone flows in both time and space (Fig. 3D) suggests that they belong to the contaminated magma type. The flows of eruptive period D form a sequence from older, relatively lower silica flows to younger, higher silica flows, a unique compositional trend if compared to compositional trends for other eruptive periods.

Eruptive Period C

The major-element compositions of the Sentinel, Fissure Butte, Sheep Trail Butte, and South Echo flows are similar to those of fractionated lava flows of eruptive period H and of the Lava Creek flows (Fig. 6; Kuntz and others, 1985). These flows, which form a sequence from older, higher silica flows to younger, lower silica flows (Fig. 6), were followed by the contaminated Sawtooth, Indian Wells North, and Indian Wells South flows. Both fractionated and contaminated lava flows, therefore, were erupted from vents spaced only a few kilometres apart along the Great Rift (Fig. 3C) over a short period of time in eruptive period C. The eruptive fissure that extended northwest to Big Cinder Butte at the end of eruptive period C may have tapped the source of contaminated magma that had led to the eruptions from Silent Cone ~500 yr earlier.

Eruptive Period B

None of the lava flows of eruptive period B contain disequilibrium minerals or textures in thin section, even though they have as much as 53.3% SiO₂; they are judged to be of the fractionated magma type. (The significance of this relationship is discussed in the next section.) These flows show a general trend from older, higher silica flows to younger, lower silica flows (Fig. 6).

Eruptive Period A

The lava flows of eruptive period A have a remarkable range in chemical composition (Kuntz and others, 1985), as represented by their SiO₂ contents (Fig. 6). The period began with the eruption of the Highway, Devils Orchard, and Serrate flows. These flows have SiO₂ contents of 54%–64%, and all show strong evidence of contamination in the form of disequilibrium minerals and textures. The younger flows of period A (Big Craters through Broken Top) have SiO₂ contents of 52% or less, and they form part of a flow sequence that became lower in silica content with time (Fig. 6).

COMPOSITIONAL VARIATION OF CRATERS OF THE MOON FLOWS IN TIME AND SPACE

The trend of line A–A' (Fig. 6), which connects the most silicic flows of the contaminated magma type, and the petrographic evidence cited earlier argue that the contaminated magma type changed composition from a parent magma

that had a composition represented by flows of eruptive period H, through the Sunset-Carey flows of period G, the Silent Cone flows of period D, the Indian Wells-Sawtooth flows of period C, to the Highway-Devils Orchard-Serrate flows of period A. The slope of line A–A' indicates that the contaminated magma type increased in SiO₂ content by ~1.5%/1,000 yr. The Sunset-Carey flows are part of the fractionated magma type based on the chemical and petrographic criteria cited earlier, but these flows are believed to be part of the contaminated magma type and too little time had elapsed before eruption for contamination processes to change their SiO₂ contents significantly.

Line B–B' generally separates contaminated and fractionated flows in Figure 6, although there is some overlap in individual analyses in the later eruptive periods. The trend of line B–B' shows that fractionated magmas have changed composition from a parent magma that had a major-element composition represented by lava flows of period H through flows of periods F, E, and C and the Big Craters through Broken Top flows of period A. The slope of B–B' indicates that the fractionated magma type increased its SiO₂ content by ~0.5%/1,000 yr.

The Rangefire and Larkspur Park flows of eruptive period B are unusual in that they have major-element compositions that are similar to compositions of flows that are representative of the contaminated magma type, such as flows of eruptive period D (Kuntz and others, 1985); yet these flows contain no xenoliths or xenocrysts. The magma source that fed flows for eruptive period B had not produced flows in the earlier history of the Craters of the Moon lava field. These relations suggest that some of the magma beneath the southern part of the Craters of the Moon segment of the Great Rift changed composition from a parent magma with a SiO₂ content of ~45% to a "contaminated magma" with a SiO₂ content of ~52%, largely by crystal fractionation. If the long-term rate of change of SiO₂ content for the fractionated magma type is assumed, then the magma source for flows of eruptive period B may have fractionated for ~18,000 yr before eruptive period B began. Alternatively, the Rangefire and Larkspur Park magmas may have developed major-element compositions that were created by contamination of more-primitive magma by xenocrysts and xenoliths that were completely dissolved or by the addition of holohyaline partial melt.

The general trend from older, lower-silica flows to younger, higher-silica flows in the evolution of the Craters of the Moon lava field has even more significance if interpreted in light of

the geographic distribution of the vents for certain magma types. For the purposes of this interpretation, we divide the Craters of the Moon segment of the Great Rift into three parts. The northern part extends from the Lava Creek vents to Big Cinder Butte, the central part extends from Big Cinder Butte to Sheep Trail Butte, and the southern part extends from Sheep Trail Butte to the buried vent complex for the Minidoka flows (Fig. 1). The contaminated magma type erupted from vents at Big Cinder Butte, Silent Cone, Big Craters, North Crater, and Sunset Cone, only on the northern part. The fractionated magma type has been erupted from vents on the northern, central, and southern parts. The Snake River Plain magma type is represented by the Kings Bowl–Wapi flows of the southern end of the Great Rift.

Magmas that have SiO_2 contents of $\sim 46\%$ or less accompany more silica-rich magmas in nearly all eruptive periods, which suggests (1) that magma reservoirs are vertically zoned, (2) that magma reservoirs are replenished by relatively silica-poor magma, and (3) that most eruptions remove more-fractionated magma at the top of the reservoir early in an eruptive period and remove less-fractionated, relatively silica-poor magma lower in the reservoir at the end of the period.

It should be noted that these preliminary conclusions about the evolution of the contrasting magma types are based on a qualitative evaluation of major-element and petrographic data and have not yet been tested by more rigorous quantitative methods.

AREAS AND VOLUMES OF LAVA FLOWS

Areas of lava flows were determined by polar planimeter from 1:125,000-scale geologic maps. The volume of each flow was determined by multiplying its area by an average thickness for each type of lava flow (Table 2). Field measurements and topographic profiles indicate that the average thickness for shelly pahoehoe flows from fissure eruptions is 5 m; tube- and surface-fed pahoehoe flows, 10 m; a'a flows, 15 m; and block-a'a flows, 20 m. Uncertainty in area determinations stems from our inability to make accurate estimates of the areas of older flows that are now largely covered by younger flows. In such cases, buried contacts were extrapolated back to known or reasonably inferred source vents. Errors in estimates of volume of flows in individual eruptive periods are judged to range from as high as 50% for eruptive periods H through B to as low as 25% for eruptive period A. Overestimates and underestimates of areas,

TABLE 2. AREAS AND VOLUMES OF LAVA FLOWS IN THE CRATERS OF THE MOON, KINGS BOWL, AND WAPI LAVA FIELDS, IDAHO

Eruptive period and flows	Estimated area (km ²)	Average thickness (m)	Estimated volume (km ³)
<i>Period A</i>			
Broken Top	11	10	0.1
Blue Dragon	280	12	3.4
Trench Mortar Flat	6	5	0.03
North Crater	1.5	5	0.01
Big Craters	9	5	0.05
Serrate	21	20	0.4
Devils Orchard	5	20	0.1
Highway	1.5	20	0.03
Kings Bowl	3	3	0.01
Wapi	330	75	6
<i>Period B</i>			
Vermillion Chasm	20	5	0.1
Deadhorse	8	5	0.04
Devils Cauldron	90	10	0.9
Minidoka	250	12	3.0
Larkspur Park	110	12	1.2
Rangefire	100	10	1.0
Blacktop Butte	<1	5	<0.01
<i>Period C</i>			
Indian Wells North	13	15	0.2
Indian Wells South	6	15	0.1
Sawtooth	37	15	0.6
South Echo	3	10	0.03
Sheep Trail	45	10	0.5
Fissure Butte	6	10	0.06
The Sentinel	30	10	0.3
<i>Period D</i>			
Silent Cone	9	15	0.1
Carey Kipuka	40	15	0.6
Little Park	70	15	1.0
Little Laidlaw Park	50	15	0.8
<i>Period E</i>			
Grassy Cone	120	10	1.2
Laidlaw Lake	70	15	1.0
Lava Point	175	15	2.6
<i>Period F</i>			
Pronghorn	80	10	0.8
Bottleneck Lake	135	10	1.4
Heifer Reservoir	40	10	0.4
<i>Period G</i>			
Sunset	100	10	1.0
Carey	230	12	2.8
Lava Creek	70	10	0.7
<i>Period H</i>			
All flows	440	10	4.4

thicknesses, and volumes of flows probably cancel each other out in determining the volume of flows for each eruptive period; thus, errors are thought not to be cumulative in determining the cumulative volume of flows and total volume of the Craters of the Moon lava field.

MAGMA OUTPUT RATES, REPOSE INTERVALS, AND STEADY-STATE VOLCANISM

"Magma output rate" is used here to denote the long-term, time-averaged discharge rate. Figure 7A shows the relation between cumulative volume of erupted lava flows as a function of time for eruptive periods H through A.

A linear, *volume-predictable* relation exists for eruptions along the Craters of the Moon segment of the Great Rift; that is, the volume of an eruption is proportional to the length of the prior repose interval and the long-term output rates. The output rate of noncontaminated lava flows was remarkably uniform at $\sim 1.5 \text{ km}^3/1,000 \text{ yr}$ for the period from 15,000 to 7000 yr B.P. About 7,000 yr ago, the total output rate increased to $\sim 2.8 \text{ km}^3/1,000 \text{ yr}$ (Fig. 7A). The increase largely reflects the addition of contaminated lava flows to the relatively constant supply of fractionated lava flows. The northern part of the Craters of the Moon segment of the Great Rift has had an output rate of $\sim 1.2 \text{ km}^3/1,000 \text{ yr}$ (Fig. 7B), and the rate for the central part of

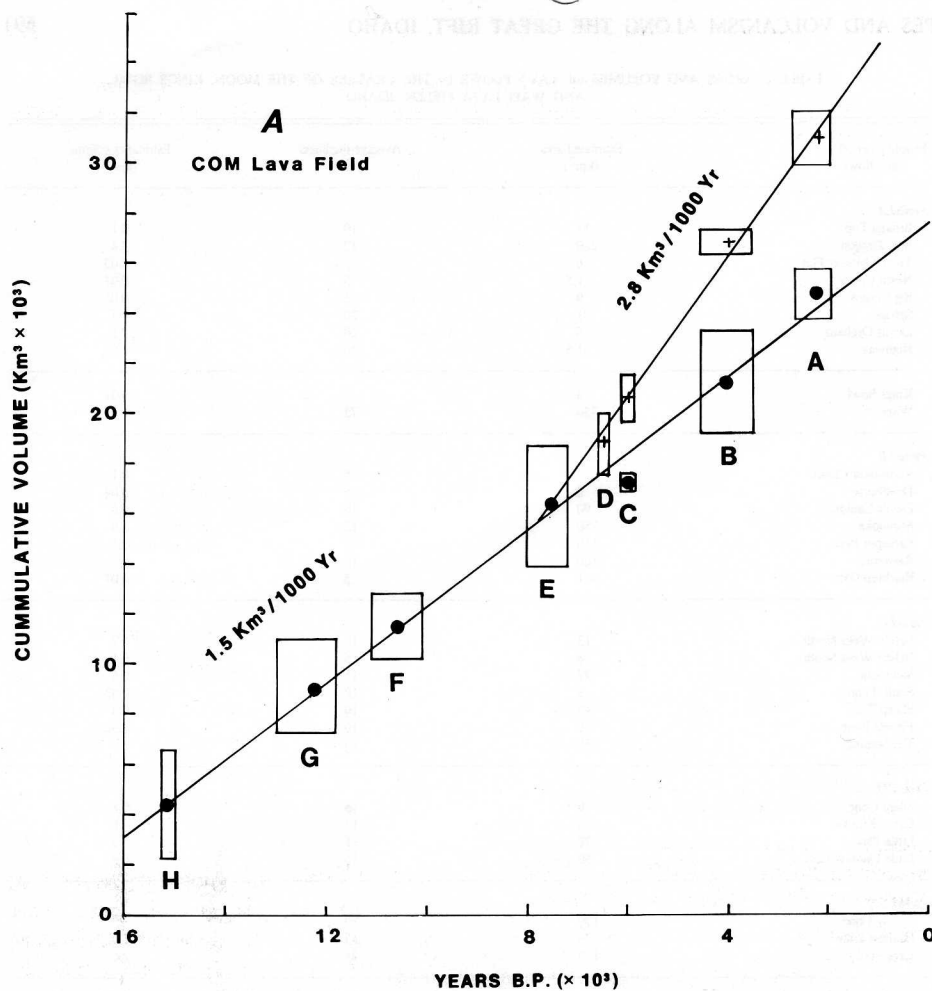
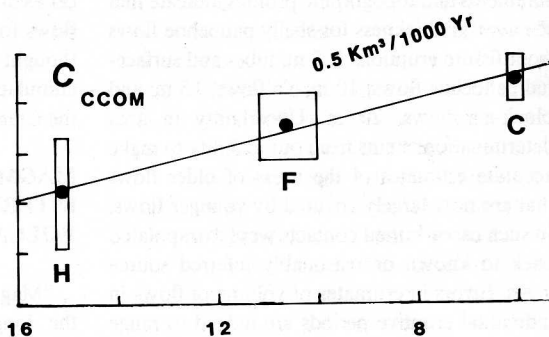
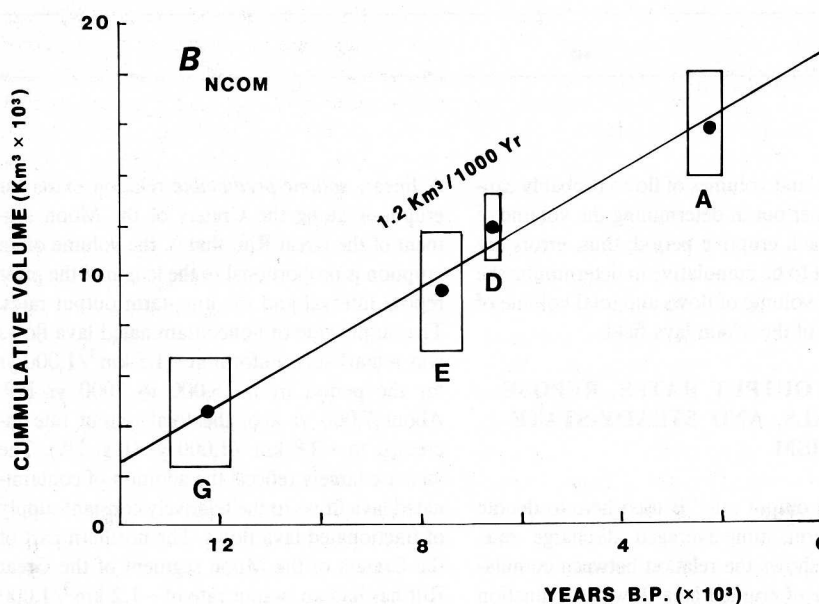


Figure 7. Cumulative volume of lava versus age of eruptive periods for the Craters of the Moon lava field. Data plotted for (A) entire Craters of the Moon segment of the Great Rift (abbreviated COM Lava Field), (B) the northern part of the Craters of the Moon segment of the Great Rift (NCOM), and (C) the central part of the Craters of the Moon segment of the Great Rift (CCOM). For Figure 7A, dots show data for fractionated magma, + shows data for fractionated plus contaminated magma, and letters refer to eruptive periods. For Figures 7B and 7C, dots refer to both fractionated and contaminated magma and letters refer to eruptive periods. Precision estimates for volume represent 50% of volume for eruptive periods H through B and 25% for period A (see text for discussion); errors for age represent range of available radiocarbon dates for each eruptive period (Table 1). The age plotted for each eruptive period is unweighted average of available radiocarbon dates for that period.



the Craters of the Moon segment of the Great Rift has been $\sim 0.5 \text{ km}^3/1,000 \text{ yr}$ (Fig. 7C), for the past 15,000 yr.

Eruptions along the Craters of the Moon segment of the Great Rift have occurred approximately every 2,000 yr, although repose intervals between eruptive periods have been as long as $\sim 3,000 \text{ yr}$ and as short as $\sim 500 \text{ yr}$ (Table 1). This relationship, in addition to the volume predictability, has important implications for the magma storage and delivery system. Evidently, an interval of $\sim 2,000 \text{ yr}$ is necessary for a complex interplay of driving forces to occur that produces eruptions along the Craters of the Moon segment of the Great Rift. The driving forces are probably related to buildup of magmatic driving pressure and regional extension of the crust or, more likely, to a combination of these forces.

Bacon (1982) wrote that the Coso, California, volcanic system is time-predictable because eruptions commence when the magnitude of some property that increases at a constant rate, such as extensional strain, reaches a critical value. He also suggested that volume-predictable eruptions stop when magmatic pressure is reduced to some constant value that is related to thickness of overburden and degree of differentiation and that the volume of magma erupted and injected as dikes is large compared to a reservoir volume that is supplied at a constant rate.

Wadge (1982) found that several composite volcanoes of different compositions display what he termed "steady-state" volcanism, that is, their plots of cumulative volume of erupted magma are linear with respect to time. He noted that few volcanoes have been studied well enough to provide the needed information to demonstrate the steady state and that the best information comes from observations of volcanoes that have had repeated eruptions during the past 30 yr or so, such as Etna, Kilauea, Piton de la Fournaise, and Fuego. The studies of Lipman (1980), however, suggest that Kilauea and Mauna Loa have not exhibited steady-state volcanism during the past few thousand years. Figure 7 shows that the Great Rift has had a quasi-steady-state eruptive history because it has experienced two distinct periods of constant, but different, long-term output rates.

Wadge (1982) noted that steady-state volcanism can be maintained for periods of as long as several hundred years and that there is no intrinsic reason why a steady state cannot be maintained for longer periods. Our data indicate quasi-steady-state volcanism has existed for at least the past 15,000 yr in the development of

TABLE 3. OUTPUT RATES AND REPOSE INTERVALS OF SELECTED VOLCANOES AND VOLCANIC REGIONS

Volcano-volcanic region	Output rate ($\text{km}^3/1,000 \text{ yr}$)	Range of repose intervals in years (10^3)	References
Great Rift			
15,000–7,000 yr B.P.	1.5	3.2 to 3.5	This study
7,000–2,000 yr B.P.	2.8	2.7 to 3.3	This study
Average (15,000–2,000 yr B.P.)	2.4	2.7 to 3.5	This study
Kilauea (1823–1975)	22	–0.5 to 1.2	Wadge (1982), Klein (1982)
Mauna Loa (1823–1975)	22	–0.6 to 1.2	Wadge (1982), Klein (1982)
Etna (1759–1974)	9.5	–0.5 to 1.7	Wadge (1982), Wadge (1977)
Piton de la Fournaise (1972–1981)	9.5	0 to 1.8	Wadge (1982), Ludden (1977)
Fuego (1932–1980)	16	0 to 1.7	Wadge (1982), Martin and Rose (1981)
Oshima (500–1951)	16	n.d.	Wadge (1982)
Iceland (last 10,000 yr)	500	n.d.	Swanson and others (1975)
Columbia Plateau	1,000	n.d.	Swanson and others (1975)
Coso volcanic field			
rhyolite	5.4×10^{-3}	4 to 5.6	Bacon (1982)
basalt	2.8×10^{-3}	4.6 to 5.8	Bacon (1982)

the Craters of the Moon lava field. Nakamura (1974) and Baksi and Watkins (1973) have shown that the output rate of volcanoes is related to their tectonic environment; output rates are greatest for intraplate-oceanic volcanoes, intermediate for volcanoes at convergent plate margins, and least for intraplate-continental volcanoes.

Magma output rates and length of repose intervals for the Great Rift and several volcanoes and volcanic regions are listed in Table 3. The Great Rift is similar to other composite or central volcanoes in terms of relatively constant output rate, but the Great Rift is significantly different in that its output rates are lower and its repose intervals are longer than are examples cited by Wadge (1982). The output rate for the Great Rift is about equal to or slightly less than that of most composite volcanoes, ~ 10 times less than the rate for Hawaiian volcanoes, ~ 20 times less than the rate for Iceland, and ~ 40 times less than the inferred rate for the Columbia Plateau (Table 3). As noted above, our radio-carbon data give estimates of the maximum repose intervals but fail to provide information about minimum repose intervals for eruptions along the Great Rift. The data in Table 3, however, suggest that the Great Rift represents an intermediate position in a spectrum of repose intervals that are characteristic of volcanoes of different tectonic environments.

The output rate and length of repose intervals for volcanism along the Great Rift and for other predominantly basaltic volcanoes and volcanic regions (Table 3) contrast markedly with the lower output rates and longer repose intervals for the bimodal volcanism of the Coso volcanic field (Bacon, 1982). This difference is probably related to the high extension rate in the Coso area, which causes numerous events of passive injection of magma in dikes that never reach the surface; thus, much of the magma that leaks from the Coso magma reservoir is stored in roof rocks. This argument suggests a lower extension rate and a larger ratio of erupted magma/stored magma for the Craters of the Moon volcanic system. These factors and the volume predictability of eruptions of the Craters of the Moon lava field suggest that buildup and decrease of magmatic pressure control the onset and termination of eruptions, respectively. Eruptions begin when magmatic pressure exceeds a critical value related to the sum of the least principal compressive stress and the tensile strength of roof rocks. If a constant supply rate of magma to a holding reservoir is assumed, then longer repose intervals suggest that more magma (larger reservoir?) is necessary to create the critical magmatic pressure to initiate the eruption, and shorter repose intervals suggest that less magma (smaller reservoir?) need be supplied to create the pressure necessary to initiate an eruption.

Eruptions end when the magmatic pressure falls below some critical value related to overburden thickness.

SPECULATIONS ON FUTURE ERUPTIONS

It is speculative to predict the time and character of future eruptions based on the past history of a volcano or volcanic rift zone, although the data presented here suggest that reasonable forecasts for future volcanism along the Great Rift can be formulated. The recurrence interval of eruptive activity for the Craters of the Moon lava field ranges from several hundred to ~3,000 yr and averages ~2,000 yr (Table 1). Because it has been ~2,200 yr since the last eruption, we are near the end of a normal repose interval, and another eruptive period seems likely within the next 1,000 yr. The steady-state nature of the volcanism and the constancy of the most recent output rate (Fig. 7) suggest that 5 to 6 km³ of lava will be erupted in the next eruptive period.

In the past, successive eruptions have generally shifted to parts of the Craters of the Moon segment of the Great Rift that have experienced the longest repose interval. This factor suggests that the next eruptive period will begin on the central part of the Craters of the Moon segment but may well propagate to the northern part of the Craters of the Moon segment of the Great Rift. The SiO₂-versus-age relationship (Fig. 6) suggests that noncontaminated lava flows with SiO₂ contents as high as 54% will be erupted first and will be followed by flows with decreasing SiO₂ contents. These eruptions would be relatively nonexplosive and would likely produce large-volume pahoehoe flows.

Eruptions from potential vents on the northern part of the Craters of the Moon segment of the Great Rift may produce lava flows of the contaminated magma type with SiO₂ contents as high as 66%. The eruption of lavas of this composition may be comparatively explosive and may be accompanied by more than normal amounts of tephra, destruction of cinder cones by collapse and explosions, and emplacement of domes.

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