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Unique Tholeiitic Lavas at Craters of the Moon, Idaho:  
G. T. Stone, M. Prinz, W. P. Leeman, C. J. Vitaliano, and J. G. Murtaugh

(Draft to be expanded somewhat  
with more data)

Stone and others

Craters of the Moon/Museum records

## Unique Tholeiitic Lavas at Craters of the Moon, Idaho

Abstract. Late Pleistocene and Holocene lavas at Craters of the Moon in the eastern Snake River Plain are extraordinarily enriched in  $P_2O_5$ , total iron, alkalis, Ba, Ga, Y, Zr, rare-earth elements, and radiogenic strontium. The series is silica-saturated and ranges from basic "olivine-tholeiitic andesite" containing fluorapatite microphenocrysts ("apatite basalt") to less abundant "tholeiitic latite." Chemical and mineralogical data indicate that Craters of the Moon and similar unusual lavas in the Snake River Plain are related to associated Snake River olivine tholeiites dominantly by fractional crystallization. Variation within the Craters of the Moon series also expresses control by crystal fractionation. Contamination probably was not important in its petrogenesis (except as a possible source of  $Sr^{87}$ ).

Craters of the Moon lava field comprises several hundred square miles of remarkably fresh basaltic lavas on the northwest side of the eastern Snake River Plain (Fig. 1). Numerous pahoehoe and aa flows radiate from the Great Rift, an alignment of cones and fissures that extends 34 miles (1) southeastward from the Pioneer Mountains (Fig. 2). The striking features of basaltic volcanism preserved in Craters of the Moon National Monument were first described in detail by Russell (2, 3), and later by Limbert (4), Stearns (5-7), and Murtaugh (8). Stearns recognized 88 volcanic vents, 39 lava flows, and 14 fissures bordered by spatter cones near the Great Rift and attributed them to three periods of volcanic activity (7). Murtaugh distinguished four eruptive episodes represented by more than 50 flows (8).

The deceptively youthful appearance of the freshest lavas led Russell (2) and Stearns (6, 7) to suggest that they erupted no more than 150 and 250 to 1,000 years ago respectively. However, an age of about 1,500 years estimated by growth-ring count for a limber pine rooted in a crack on the North Crater pahoehoe flow (9), one of the youngest lavas in the Monument, led Stearns to propose an age of at least 1,650 years for its eruption (10). This is consistent with a radiocarbon date of  $2,130 \pm 130$  years B.P. obtained for charred sagebrush found beneath the lowest flow from the King's Bowl rift about twenty miles to the south-southeast (1). Further confirmation of the time of most recent volcanism is provided by the essentially identical radiocarbon date of  $2080 \pm 85$  years B.P. reported for charcoal rootlets from beneath lava erupted "late in the volcanic history of the area" about seven miles southeast of the Monument boundary (11). Comparison to the degree of erosion and amount of soil and vegetative cover of the Snake River Group basalts (12, 13) suggests that

some of the oldest cones and flows in and near Craters of the Moon are of late Pleistocene age, and probably at least 30,000 years old (14).

Hillebrand's whole-rock analysis (2, 15) first revealed silica-saturated basaltic lava highly enriched in iron, alkalis, and phosphorus at Craters of the Moon (Table 1, sample 12). Anderson (16) characterized aa from Lava Creek vents as "normal olivine-free basalt," but Williams (17) perceived the iron-rich composition of other Craters flows which he described as "olivine basalt abnormally rich in magnetite" and in which "the olivine probably contains much iron." Murtaugh, recognizing a diversity of lava composition in the Monument, termed the pahoehoe and aa flows, "olivine basalt"; the block lavas, "andesitic basalt"; and a thin flow exposed in the Highway fault scarp, "andesite?" (8). He noted a paucity of pyroxene in the basalts but observed a few pyroxene microphenocrysts and sanidine xenocrysts in the andesitic rocks. Stone pointed out an abundance of apatite, especially as microphenocrysts, in the Sunset Cone (west?) and other flows (18), and called attention to the chemical variation and marked iron, phosphorus, and alkali enrichment of Craters lavas (19).

Sixteen previously unpublished (20) analyses of samples collected at Craters of the Moon (21) establish the compositional range and major-element characteristics of this distinctive volcanic series (Table 1). The thirteen most basic analyses representing at least eight different flows show relatively little chemical variation; the four most silicic analyses (samples 14-17) representing only three lavas greatly extend the compositional range. The more uniform basic lavas apparently predominate at Craters of the Moon. Although none of the basic whole-rock analyses passes Manson's chemical screen for basalts (22), eleven are

within all of his oxide limits except the maximum of 1.50 weight percent  $P_2O_5$ . This emphasizes the extraordinarily high phosphorus content of the Craters of the Moon series; the eleven most basic whole-rock analyses range from 1.59 to 2.52 and average 1.92 weight percent  $P_2O_5$ . Generally, phosphorus, along with titanium and alkalis, is more abundant in alkalic basalts (23), and the more basic Craters of the Moon lavas resemble some hawaiites and mugearites in their high concentrations of these elements (24). However, the same constituents may be enriched in tholeiitic liquids (25), and the progressive increase of silica saturation expressed by the normative mineralogy of the Craters series (Table 1) establishes its tholeiitic character (19).

Six of the analyses presented in Table 1 are olivine- and hypersthene-normative, one is hypersthene-normative with neither normative olivine nor quartz, and ten are hypersthene- and quartz-normative. Even the highest normative olivine-hypersthene ratio, 12.99/7.56 (sample 2), is well within the olivine-tholeiite region of the normative basalt tetrahedron (26). The low ferric-ferrous oxide ratios of the thirteen most basic Craters analyses (average =  $2.31/13.30 = 0.174$ ) are characteristic of tholeiitic series (27) and show that the availability of silica in the norms has not been significantly increased by secondary oxidation of iron. Samples 1-4 and 6 might better be considered highly evolved, olivine-tholeiitic andesites rather than basalts because of their iron- and alkali-enriched compositions. Nockolds' "average alkali andesite," for example, contains comparable silica and alkalis (with slightly more  $Na_2O$  and less  $K_2O$ ), although it is nepheline-normative and less iron-enriched (28). Similarly, analyses 5 and 7-13 may be characterized as iron-, potassium-, and phosphorus-enriched tholeiitic andesites.

The four most silicic Craters analyses (Table 1, samples 14-17) represent slightly quartz-normative, iron-enriched, intermediate rock types. The analysis of sample 14 lies roughly between iron-rich counterparts of Daly's average "trachyandesite" (29) and Nockolds' average "hornblende-biotite monzonite" (28). It somewhat resembles Hawaiian benmoreites, (27, 24), but the latter are much less iron-rich, much more oxidized (resulting in appreciable quartz in some norms), and considerably richer in  $Al_2O_3$  and  $Na_2O$  (with less  $K_2O$ ). The analyses of samples 15-17 are similar in  $SiO_2$ ,  $K_2O$ , and  $MgO$  content to soda trachytes of the Hawaiian alkalic suite, but closer to rhyodacites of the tholeiitic suite in  $Al_2O_3$ ,  $Na_2O$ , and normative quartz (30). However, the Craters rocks are distinctly more iron-rich than either Hawaiian type. It seems reasonable to consider the Devil's Orchard flow (sample 14) an alkali-enriched tholeiitic andesite, but "iron-enriched tholeiitic latite" is probably more appropriate for samples 15-17.

The unusual chemical compositions of the Craters of the Moon suite clearly make the application of common volcanic-rock names difficult. The entire series is characterized by extreme iron enrichment ( $F/F+M = 0.77$  to  $0.98$ ), moderate to high alkali enrichment ( $A/A+C = 0.40$  to  $0.74$ ), and increasing silica saturation (Table 1). Moreover, it shows extreme  $P_2O_5$  concentration in its basic members (up to 2.52 weight percent) and very high  $K_2O$  concentration in its most silicic rocks (up to 4.72 weight percent). The alkali-lime index of the series is approximately 52, so it is an alkali-calcic series according to Peacock's classification (31).

The highest total-iron content (as  $FeO$ ) of the analyzed Craters of the Moon samples, 16.39 weight percent (Table 1, sample 1), is comparable to

that of the Skaergaard liquid after about 80 percent solidification, but the range of iron enrichment ( $F/F+M$ ) of the lavas (Table 1) corresponds to that of the last 10 percent of Skaergaard liquid (32). Skaergaard liquids reached a maximum  $P_2O_5$  percentage of about 1.75 (and layered-series rocks, 2.5) when approximately 97 percent solidified but apparently did not approach the high alkali concentrations (particularly  $K_2O$ ) of the Craters lavas until more than 99½ percent solidified. The "solidification index" (33) of the Craters series ranges from 0.18 to 0.01.

The tholeiitic Thingmuli volcanic series of Iceland is almost as iron-enriched as the Craters of the Moon suite but generally contains much less  $K_2O$  and  $P_2O_5$  (34). However, lava on Eggjar Ridge (G. 84) is relatively rich in  $P_2O_5$  (0.99 weight percent), and iron-rich andesites ("icelandites") are considerably enriched in alkalis (up to 4.72%  $Na_2O + 2.75\% K_2O$ ). Olivine basalt from the Icelandic volcanoes Eldgja and Katla (35) and Late Yakima basalt of the Columbia River Plateau (36, Table 4, column 3) also approach the high iron enrichment of basic Craters lavas but contain much less  $K_2O$  and  $P_2O_5$ , and the Eldgja-Katla basalts have more  $CaO$ . Similarly, "segregation veins" in prehistoric Kilauea tholeiite (33, Table 5, column 6) and high-alumina Warner basalt (37, Table 3, column 6D) approximate basic Craters lavas in iron enrichment but are poorer in alkalis (especially  $K_2O$ ) and  $P_2O_5$ . Hawaiites of Skye (38) are nearly as iron-enriched as the most basic Craters flows but have much less  $K_2O$  and  $P_2O_5$ , and, like lavas of the Hawaiian alkalic suite (24), contain more  $Na_2O$  and  $Al_2O_3$  and are nepheline-normative. A marked rise of alumina content is common in alkalic series, whereas relatively constant alumina, as in the Craters of the Moon suite, is characteristic of tholeiitic series (33, 38).

Although lavas of the John Day series in north-central Oregon approximate the high iron- and alkali-enrichment of the Craters series (39), they are comparable in  $P_2O_5$  content only to its relatively silicic rocks (55-59%  $SiO_2$ ) and are significantly poorer in  $K_2O$ . Some Steens Mountain basalts of southeastern Oregon are chemically similar to moderately basic Craters lavas (48-50%  $SiO_2$ ) but contain much less  $P_2O_5$  (40). Average Nuanetsi basalt (with  $MgO < 5\%$ ) of the northern Karroo province approaches the iron and alkali content of intermediate Craters lavas (53%  $SiO_2$ ), but is somewhat richer in  $MgO$  and poorer in  $P_2O_5$  and  $Na_2O$  (41). Quenched ooze from Alae lava lake also resembles middle compositions in the Craters series but contains slightly less  $K_2O$  (42). The Umatilla flow of the Yakima basalt in south-central Washington comes closest to matching intermediate compositions of the Craters series (43).

The most unusual characteristic of the Craters suite clearly is the extreme enrichment of  $P_2O_5$  in its most basic lavas. To our knowledge, only the "mafic mugearite" from East Molokai containing 2.39 weight percent  $P_2O_5$  (24, Table 2, column 9) approximates the  $P_2O_5$  content of the most basic Craters flows, but it is much less iron-enriched, much more oxidized, nepheline-normative (7.38%), and contains significantly more  $Al_2O_3$  and  $Na_2O$ . Residual liquid from Alae lava lake contains 2.0 percent  $P_2O_5$  and 5.1 percent  $K_2O$ , but has 72.0 percent  $SiO_2$  (44). Mugearites of the Kohala Kawi series (24, Table 3, columns 11 and 12) and trachyte from Kodiak Seamount (45) contain almost two percent  $P_2O_5$ , but otherwise differ markedly from Craters lavas.

This brief survey reveals that a few volcanic rocks approximate the high iron- and alkali-enrichment shown by members of the Craters series,

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and one (Umatilla basalt) also matches the high  $P_2O_5$  content of its intermediate members, but none shares the distinctive combination of comparatively low  $SiO_2$  content, very high iron enrichment, high  $K_2O$  and extreme  $P_2O_5$  concentration shown by its most basic flows. The only lavas that approach the combined chemical peculiarities of the Craters suite are also within or marginal to the Snake River Plain (and are described in the following paragraphs). The Craters of the Moon lava series apparently is unique as an extreme example of its type.

Three superposed basaltic flows that form a caprock north of King Hill in the western Snake River Plain (2, 46) are chemically very similar to Craters of the Moon lavas. The King Hill flows are the second youngest lavas of the Middle Pleistocene Bruneau Formation (12) and erupted about 85 miles west of the Great Rift at Craters of the Moon along the northern margin of the Snake River Plain. The youngest lava of the Bruneau Formation was dated at 1.36 million years by the potassium-argon method (47). Powers first described King Hill rocks (48) giving the average and range of five major-oxide analyses and noting high percentages of total iron (as  $FeO$ , 15.45-13.27),  $TiO_2$  (4.15-2.90),  $K_2O$  (2.00-2.60), and  $P_2O_5$  (2.05-0.90), and low  $MgO$  (4.42-3.33) and  $CaO$  (7.68-6.36) for comparatively low  $SiO_2$  (47.17-51.23). Stone (18) outlined the petrography of the flows and presented Powers' five analyses plus a sixth which extends their range to 60.38 percent  $SiO_2$  and 8.10 percent total alkalis ( $3.89 Na_2O + 4.21 K_2O$ ). The compositional range of King Hill lava is only slightly narrower than that of the Craters series, and both exhibit the same remarkable combination of chemical characteristics. Although the King Hill series is somewhat richer in  $TiO_2$ , it is slightly less iron-enriched ( $F/F+M = 0.78-0.88$ ) and poorer in  $P_2O_5$ .

Lava along the Blackfoot River canyon (49, Pl. 61, B) about 75 miles east of Craters of the Moon near the southern margin of the eastern Snake River Plain is chemically almost identical to moderately basic members of the Craters series. Basaltic flows in this drainage probably erupted from vents near Blackfoot River Reservoir 25 miles farther southeast (49, p. 128). An analysis of Blackfoot River lava (Table 2, sample 27) essentially matches analyses of the North Crater pahoehoe flow (especially sample 8, Table 1) and the Indian Tunnel flow (Table 1, sample 10) differing only in its slightly higher CaO and slightly lower Na<sub>2</sub>O percentages (resulting in 4.27% normative quartz).

The Blackfoot River locality is just six miles north of the collection site of "nepheline basalt" described by Mansfield and Larsen (50). However, their peculiar forsterite-diopside-biotite rock containing more than eleven percent normative nepheline differs vastly in composition from any lava reported in the Snake River Plain (51), and they concluded that it "probably was not closely connected with the olivine basalts" exposed in the canyon of the Blackfoot River (50).

An "odd mafic latite" of late Pleistocene age from Antelope Flat on the western rim of the Island Park caldera chemically resembles the most silicic Craters of the Moon lavas 115 miles to the southwest (52, Table 1, column 4). It is closer to Craters sample 16 in SiO<sub>2</sub>, TiO<sub>2</sub>, and MgO, but more like sample 17 in total iron and alkalis, CaO, and P<sub>2</sub>O<sub>5</sub> (Table 1). It is slightly less iron-enriched ( $F/F+M = 0.94$ ) than silicic Craters rocks (like King Hill lava) but somewhat more alkali-enriched ( $A/A+C = 0.78$ ). The greatest chemical difference is the two-percent higher Al<sub>2</sub>O<sub>3</sub> content of the Antelope Flat lava (16.34).

Most of the basaltic lavas in the western Snake River Plain are comparatively uniform, iron-rich, olivine tholeiites (53, 18). The nine major-oxide analyses of Snake River basalts (56) in Table 2 are from a variety of localities in the central and eastern Plain (Fig. 1) and broadly conform to the compositional characteristics of the western suite (57). For relatively low-SiO<sub>2</sub> basalts (44.18-47.35%), most are comparatively rich in total iron, TiO<sub>2</sub>, and P<sub>2</sub>O<sub>5</sub>, but poor in total alkalis and MgO. Anomalously high percentages of Al<sub>2</sub>O<sub>3</sub> characterize samples 20 (16.10) and 25 (16.21); high CaO (12.30) and Na<sub>2</sub>O (3.06), sample 18; and exceptionally high Na<sub>2</sub>O, sample 26 (3.89). The last three analyses are slightly nepheline-normative. Although Stone noted that the low-hypersthene, high-olivine norms of two basalts in the western Snake River Plain "appear to be transitional to alkali basalt" (18, p. 284), samples 18, 25 and 26 are the first critically undersaturated Snake River basalts to be reported.

Slight systematic chemical variation is evident among the basalts of Table 2, particularly in their ranges of iron enrichment, TiO<sub>2</sub>, K<sub>2</sub>O, and P<sub>2</sub>O<sub>5</sub>. The analyses are tabulated in order of increasing P<sub>2</sub>O<sub>5</sub> percentage to indicate the order and range of liquid-crystal fractionation stages represented (58). Potash shows striking positive correlation with P<sub>2</sub>O<sub>5</sub>, and TiO<sub>2</sub>, iron enrichment, and alkali enrichment also are generally higher in the more fractionated lavas. Silica, however, is more abundant in the less fractionated basalts (samples 18-21). The Snake River basalts overlap basic Craters of the Moon lavas in SiO<sub>2</sub>, TiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub> percentages, but contain much more MgO and CaO, less total iron, slightly less Na<sub>2</sub>O (except sample 26), and much less K<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub> (Tables 1 and 2). These major-oxide

differences demonstrate that the Snake River basalts have significantly less fractionated compositions than the lavas at Craters of the Moon.

Minor- and trace-element data obtained by a variety of analytical techniques for ten samples from Craters of the Moon and the sample of Blackfoot River lava are presented in Table 3. As in Table 1, the Craters data (samples 1-17) are tabulated in order of increasing  $\text{SiO}_2$  content to reveal correlative changes. A notable trend is the coupled decrease of F and slight increase of Cl in the series. Barium, Be and Rb are progressively concentrated, whereas Sr, ignoring semiquantitative data, appears to become depleted. Yttrium shows a slight but steady increase which is paralleled by La through sample 14, but the latter is distinctly lower in 17. The two reported concentrations of Yb (samples 6 and 17) suggest a slight increase, which also holds for the light rare earths, Ce and Nd, at least through sample 14. Zirconium, Nb, and Pb similarly are more abundant in the most silicic rocks, but Co, Cr, Cu, Ni, V and Zn are depleted. The Highway "andesite" (sample 17) is generally comparable in trace-element composition to the mafic latite of Antelope Flat, in which Ba, Zr, Nb, Y, La, Ce, Nd, and Yb are "uncommonly abundant" (52). The Antelope Flat rock, however, is much poorer in Cl, F, and Zr, and somewhat richer in La, Mo and Ni.

Zinc is unusually abundant in the Snake River basalts (average of 32 samples = 0.014%, range = 0.0093-0.0180%) and shows strong positive correlation with total iron and MnO (61). The Blackfoot River sample contains even more Zn (0.0196%), and basic Craters of the Moon lavas have twice as much (Table 3). Major- and minor-element data for four basalts in the western Snake River Plain (62) reveal that Ba, Sr, Y, Ga, and Zr also

show significant positive correlation with total iron, as well as with  $P_2O_5$  and  $TiO_2$ , whereas Cr and Ni show marked negative correlation with those constituents. Barium, Ga, and Zr are more abundant and Cr, Ni, V, and Sc less abundant in basic Craters lavas than in the Snake River basalts; Y, Sr, Cu and Co overlap. Lead, U, and Th also are enriched in Craters rocks (Table 3) compared to Snake River ("Shoeshone") basalt (63), which accounts for their high natural gamma aeroradioactivity (64). Furthermore, the relative abundance of cinder cones at Craters of the Moon suggests that volatile substances were more highly concentrated in Craters magmas than in those of Snake River basalts. In summary, minor- and trace-element abundances together with major-oxide data demonstrate that basic Craters of the Moon and similar lavas have much more fractionated compositions than the Snake River basalts (32, 65).

Compared to most basaltic rocks (65, 66), basic Craters lavas contain extraordinarily high concentrations of Ba (0.1-0.22%), Ga (0.003-0.005%), Y (0.007-0.01%), and Zr (0.05-0.09%). Some basic rocks of Hawaiian, Scottish, and Polynesian alkalic suites contain comparable amounts of Ba (67) and Zr (68, 69, 34), but to our knowledge, only basic rocks of the Braefoot Outer sill in Scotland (67) and the Cashel-Lough Wheelaun intrusion in Ireland (70) have been reported with as much Ga. Nearby Snake River basalts (62) and gabbroic rocks in the northwest part of the Idaho batholith (71), "olivine tholeiite" (D-3) from the East Pacific Rise (72), and a few Hawaiian and Hebridean mugearites (68) match their high Y concentrations. The Craters rocks are extremely depleted of Cr and Ni, and relatively low in V (65, 66).

Preliminary results indicate that the Craters of the Moon series is highly enriched in light and heavy rare-earth elements (Table 3). Of

continental basalts analyzed by Frey et al. (72), only Jefferson County, Colorado, "basalt" approaches the overall light rare-earth composition of basic Craters lava. Intermediate rocks of a number of alkalic series have comparable La concentrations (68, 69, 34, 72), a Kohala mugearite has the same Ce content (200 ppm), and the 1801 Kaupulehu alkali basalt from Hualalai contains almost as much Nd (33).

Incredibly, the "unique chemistry" of Apollo 12 sample 12013 from the real craters of the Moon (73) resembles that of Highway "andesite" from the terrestrial Craters of the Moon (Tables 1 and 3, sample 17). Comparable major oxides of 12013 include (in weight percent):  $\text{SiO}_2$  (61),  $\text{TiO}_2$  (1.2),  $\text{Al}_2\text{O}_3$  (12),  $\text{FeO}$  (10), and  $\text{MnO}$  (0.12). Even more remarkable are the similar trace-element concentrations of 12013 (in ppm): B (15), Ba (2,150), Nb (170), Pb (30), Rb (33), Sc (21), Sr (150), V (13), Y (240), Yb (20), and Zr (2,200). Unfortunately, there are significant differences. Although  $\text{K}_2\text{O}$  and  $\text{CaO}$  in 12013 are low and high respectively by a factor of only about two,  $\text{Na}_2\text{O}$  and Co are low and high by more than six times,  $\text{MgO}$  is high by a factor of 30, Ni by more than 50 times, and Cr is high by at least three orders of magnitude. Like the lavas at Craters of the Moon, all Apollo 11 samples (74) and Apollo 12 fines and breccias (73) are extraordinarily rich in Y and Zr. Tranquility Base basalts (type A) approach the Sm concentration of Craters lavas, and, like "anomalous" East Pacific Rise "andesite" (D-3), most Apollo 11 samples exceed Craters' Yb and Lu concentrations (75).

High  $^{87}\text{Sr}/^{86}\text{Sr}$  values (0.708-0.711) also distinguish Craters of the Moon lavas (60, 59, 76-78), as well as the King Hill and Blackfoot River flows (78, 77), whereas moderately high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (0.706-0.708)

characterize the Snake River basalts (80, 59, 76-79). However, lead isotopic compositions of Craters lavas and Snake River basalts are comparatively unradiogenic (63, 76).

Most samples from Craters of the Moon were collected near exposed flow surfaces and consequently are somewhat vesicular and very fine-grained with considerable glassy matrix. Textures vary from hyalopilitic and intersertal to intergranular, and subparallel flow-orientation of plagioclase laths is common (Figs. 3A and 3B). Plagioclase, olivine, magnetite, and apatite range in size in seriate fashion from microphenocrysts to microlites in basic Craters lavas (samples 1-12); the residuum comprises brown silicic glass containing crystallites and skeletal crystals of the same minerals plus augitic clinopyroxene, which forms elongate subhedra in holocrystalline specimens. Outermost zones and residuum crystals of feldspar probably are much enriched in  $K_2O$ .

Olivine and apatite are most abundant in the most basic flows. The mode of the Sunset Cone west(?) flow (sample 1) is (volume percent, 2000 points counted): plagioclase, 28.8 (up to 0.6 mm in length, average = 0.2 mm); olivine, 11.2 (1.3 phenocrysts, up to 1.6 mm in maximum diameter); magnetite, 7.2 (up to 1.0 mm); apatite, 1.9 (up to 0.6 mm in length, Figure 3A), and glassy residuum, 50.9. Apatite constitutes 3.9 percent of the crystalline fraction; it occurs as colorless, hexagonal, prismatic euhedra that have a 10:1 length:width ratio (Figure 3A). The extraordinary abundance of apatite as a microphenocryst mineral in basic Craters lavas indicates that it was a liquidus or near-liquidus phase with olivine, magnetite, and plagioclase. Conspicuous microphenocryst intergrowths of apatite with olivine (Figure 3B) and with magnetite support this

interpretation. Such lavas may appropriately be termed "apatite basalt."

Electron-probe microanalyses (Table 4) more accurately define microphenocryst compositions in the Blue Dragon and North Crater pahoehoe flows as calcic andesine ( $An_{45-43}$ ), comparatively iron-rich olivine ( $Fo_{46-40}$ ), titanomagnetite ( $Usp_{69-70}$ ), and fluorapatite ( $F/(F+Cl) = 0.95$ ). Greater enrichment of total iron (and MnO) at the expense of MgO is manifest in olivine and magnetite of the more silicic North Crater flow, which also shows slight depletion of  $Al_2O_3$  in magnetite and, coupled with slight enrichment of alkalis, in plagioclase. Crystallization of olivine accounts for the decrease of MgO in residual glass (Table 1, sample 11) of the Blue Dragon flow (sample 2). The increase of  $SiO_2$  is due to separation of magnetite and apatite; the latter also depleted the residuum of  $P_2O_5$ . Andesine crystallization effected the decrease of  $Al_2O_3$  and  $Na_2O$  in the residual glass, which is, however, almost 50 percent enriched in  $K_2O$  (Table 1).

Olivine microphenocrysts are scarce or lacking in rocks more silicic than sample 8 (Table 1), and apatite microphenocrysts are absent in rocks more silicic than sample 12. Plagioclase and magnetite apparently were the liquidus minerals of most of these more silicic lavas. Apatite is restricted to the residuum of the Devil's Orchard flow (sample 14) and is not evident in the Highway "andesite" (sample 17).

Although augite appeared relatively late in the paragenesis of basic Craters lavas (after 50 percent crystallization), it is present as seriate microphenocrysts and probably began to crystallize with or shortly after olivine in the Devil's Orchard flow, which also incorporates partially

resorbed andesine phenocrysts. The finely vesicular Highway "andesite" contains microphenocrysts of light-green hornblende and scarce pale-green olivine (like the Antelope Flat latite, 52) in addition to, like the most silicic King Hill lava (18), partially absorbed xenocrysts of anorthoclase (grid-twinning, moderate 2V) and sodic sanidine (untwinned, low 2V) in a very fine-grained matrix of feldspar laths (average length = 0.06 mm; undoubtedly transitional to alkali feldspar), prismatic mafic microlites, magnetite cubes, and turbid residuum of brownish silicic glass and cryptocrystalline material. Vesicles are generally surrounded by oxidation halos and commonly have hemispheres of radiating low-cristobalite crystals on their walls.

Basic Craters of the Moon lavas differ in paragenesis from Snake River basalt (53, 18) in their early crystallization of apatite and titanomagnetite, and in their lack of ilmenite and picotite. Clinopyroxene characteristically was late in both sequences. The comparatively lower iron- and alkali-enrichment of the Snake River basalts is expressed by the compositions of its microphenocryst and matrix silicates (82): most plagioclase is in the labradorite range ( $An_{69-52}$ ), most olivine is comparatively forsteritic ( $Fo_{75-60}$ ), and the clinopyroxene is largely calcium-rich augite (83).

Comparison to the liquidus temperature-iron enrichment trend of tholeiitic Kilauean lavas (38, 84) suggests that the Snake River basalts represented in Table 2 (samples 18-26) began crystallizing the range 1190-1150°C ( $F/F+M = 0.60-0.68$ ), and that the basic Craters lavas of Table 1 (samples 1-13) had liquidus temperatures in the range of 1110-1060°C ( $F/F+M = 0.77-0.87$ ). The liquidus range suggested for Snake River basalts

is consistent with an estimate of  $1125^{\circ}\text{C}$  by Buddington and Lindsley (85) for the co-crystallization temperature of titanomagnetite and ilmenite in a sample of Snake River basalt, and with experimental melting data for several basalts of the western Snake River Plain (86). Liquidus temperatures reported for four Craters lavas (samples 1, 8, 10, and 14) are within the expected range (86). Estimates of liquidus temperatures for Snake River basalts based on iron enrichment in Kilauean tholeiites may be slightly low due to the lower silica content of the Snake River rocks.

The extraordinary composition of Craters of the Moon lavas, and their occurrence in the Snake River Plain where comparatively uniform olivine tholeiites predominate may at first suggest that a singular, localized process such as contamination was largely responsible for the peculiarities of the series. However, the presence of similar lavas with diverse ages in at least three other, widely separated localities within or marginal to the Snake River Plain (Antelope Flat, Blackfoot River, and King Hill) indicates that a more general, recurring process has been operative. Moreover, the consistent temporal and spatial association of these unusual lavas with Snake River basalts implies that the two types are genetically related.

As noted earlier, the chemical compositions of Craters of the Moon and similar lavas indicate that they represent more highly fractionated magmas than do the Snake River basalts. Slight chemical diversity among Snake River basalts (Table 2, samples 18-26) suggests variation in the degree of liquid-crystal fractionation of their parental magmas; marked fractionation clearly accompanies crystallization of the basalt lavas. Progressive changes in the major-oxide compositions of representative residual liquids of Snake River basalt are illustrated qualitatively in Figure 4 on the basis of inferred paragenesis and determined rock and mineral compositions (18, 82).

Initial control is by crystallization of forsteritic olivine ( $\text{Fo}_{75-70}$ ) which starts continuous depletion of  $\text{MgO}$  and enrichment of  $\text{K}_2\text{O}$  in the residual liquid and effects temporary depletion of  $\text{FeO}$  (and  $\text{MnO}$ ) and enrichment of  $\text{SiO}_2$  accompanied by enrichment of the other major oxides. Olivine is joined almost immediately by more abundant calcic labradorite which depletes the liquid of  $\text{Al}_2\text{O}_3$ , compensates for the enrichment of  $\text{SiO}_2$  and  $\text{Na}_2\text{O}$ , reverses the depletion of  $\text{FeO}$ , moderates the depletion of  $\text{MgO}$  and the enrichment of  $\text{CaO}$  and  $\text{K}_2\text{O}$ , and augments the enrichment of  $\text{Fe}_2\text{O}_3$ ,  $\text{TiO}_2$ , and  $\text{P}_2\text{O}_5$ . Crystallization of calcium rich augite after the lava is approximately half solidified initiates continuous depletion of  $\text{CaO}$ , accelerates  $\text{MgO}$  depletion, moderates the depletion of  $\text{Al}_2\text{O}_3$  and enrichment of  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$ , and  $\text{TiO}_2$ , renews  $\text{Na}_2\text{O}$  enrichment, and further concentrates  $\text{K}_2\text{O}$  and  $\text{P}_2\text{O}_5$ . Silica remains approximately constant. Titanomagnetite and ilmenite crystallization finally initiates continuous depletion of  $\text{FeO}$ ,  $\text{Fe}_2\text{O}_3$ , and  $\text{TiO}_2$  and enrichment of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . Later crystallization of apatite augments  $\text{SiO}_2$  enrichment and begins depletion of  $\text{P}_2\text{O}_5$ .

The nearly constant silica content and marked iron enrichment which characterize early Snake River basalt fractionation is clearly shown in Figure 5 by the trend T-G, which connects representative olivine tholeiite (T, 31% crystallized pillow lava) with its residual glass (G, 87). This trend points directly toward the more fractionated basic lavas of the Craters of the Moon (Table 1) and King Hill (18) series and suggests that they may have evolved by low-pressure fractionation of Snake River basalt magmas. Such a relationship is consistent with their relative liquidus temperatures inferred from iron-enrichment values (38, 84) and determined experimentally (86). Other major oxides of the residual glass (G) are also changed toward

basic Craters and King Hill compositions with the sole exception of  $\text{CaO}$ ; its depletion by augite crystallization had not yet been initiated.

The  $\text{P}_2\text{O}_5$  content of the olivine tholeiite (0.53%) is about one fifth of that in the Blue Dragon flow (2.52%), the maximum for Craters lavas. Thus, approximately 80 percent crystallization of such olivine tholeiite would be necessary to derive a residual liquid with as much  $\text{P}_2\text{O}_5$  as the Blue Dragon flow (58). This degree of fractionation can account for all major-oxide and known trace-element differences between Snake River olivine tholeiite and basic Craters lavas. The percentage of  $\text{P}_2\text{O}_5$  in the olivine tholeiite (T) is about average for Snake River basalts (Table 2), but if less fractionated Snake River basalt is considered as parental magma (such as sample 18), at least 90 percent crystallization is required to yield Blue Dragon lava. These estimates agree well with the general observation that modal apatite is present only in the residua of Snake River basalts that are at least 85 percent crystalline (18, Fig. 70).

Figure 5 illustrates that the Craters of the Moon series is slightly more iron-enriched than the King Hill suite. Blackfoot River lava lies on the Craters trend, but Antelope Flat latite is closer to a silica-rich extension of the King Hill trend. Early crystallization of titanomagnetite and apatite, and accompanying enrichment of silica in the preponderant basic Craters lavas suggest that the wide range of silica enrichment (Figure 5) and correlative chemical variation in the series (Table 1) are due to fractional crystallization. Other progressive chemical changes in the Craters series also are consistent with control by crystal fractionation. The decrease of fluoride (0.20-0.11%) and slight increase of chloride (0.04-0.06%) noted for these  $\text{P}_2\text{O}_5$ -rich lavas undoubtedly express preferential

incorporation of the more electronegative fluoride anion in crystallizing apatite, a fractionation effect which rarely can be documented in basaltic rocks. Chloride enrichment ( $Cl/Cl+F$ ) more than doubles through the series (0.17-0.35).

Residual glass of the Blue Dragon flow (Table 1, sample 11) differs significantly in several major oxides from Craters lavas containing comparable  $SiO_2$ . These differences are expressed normatively by less feldspar and more pyroxene in the residual glass and thereby imply that the fractionating parental magmas experienced pyroxene control that was not effective early in the paragenesis of the basic lavas themselves. Basic Craters flows probably do not correspond to direct precursors of the associated more silicic lavas, but all Craters lavas likely were tapped from a related series of fractionating parental magmas. Basic Craters and similar lavas probably are related in the same way to most Snake River basalts.

No consistent relationship between the sequence of eruptions (8) and the degree of fractionation of the analyzed lavas is apparent. The most silicic rocks (Table 1, samples 15-17) probably are the oldest, but the most basic flow (sample 1) is next oldest. The moderately silicic Devil's Orchard flow (sample 14) is younger than the Sunset Cone west(?) flow (sample 1) but older than the Big Craters northwest flow (sample 13). Among the youngest group of lavas are the basic Blue Dragon flow (sample 2) and the moderately basic North Crater pahoe-hoe flow (samples 7-9, 12). The repeated eruption of lavas representing different stages of fractionation indicates that the parental magmas were trapped in a configuration which prevented homogenization, and that either more basic magma was repeatedly introduced or fractionation progressed at markedly different rates in different places.

The high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of Snake River basalts compared to those of most oceanic basalts have been attributed to assimilation of crustal material (80, 59) and inhomogeneity in the upper mantle (76-79). Some sort of contamination is the preferred explanation of the even higher  $^{87}\text{Sr}/^{86}\text{Sr}$  values of Craters of the Moon lavas (59, 76, 78, 79). Doe (76) suggested that assimilation of dehydrated Precambrian lower crust may in part explain the high radiogenic-strontium and low radiogenic-lead compositions of Craters rocks compared to Snake River basalt (63). The common occurrence of exotic xenoliths in Craters lavas demonstrates that some contamination has taken place. Stearns (7, p. 97) observed "numerous inclusions of more or less gneissic, coarse-grained hypersthene-quartz diorite" in the Serrate flow, which also exhibits the highest natural gamma aeroradioactivity of the region (64), and Murtaugh called attention to xenoliths of "pyroxene granulites of noritic composition" in the flows of the Monument (8, p. 81). "Gneissose quartz diorite" has been reported in the Pioneer Mountains bordering Craters of the Moon on the northwest (88), so an appropriate source for the described xenoliths may underlie the lava field at a comparatively shallow depth. The existence of xenoliths in lava, however, does not establish that measurable change in the bulk chemistry of the liquid was effected. In fact, their unaltered preservation may belie significant assimilation.

In conclusion, available field, mineralogical, and chemical evidence is consistent in indicating that Craters of the Moon and similar lavas in the Snake River Plain are genetically related to the Snake River olivine tholeiites dominantly by processes of fractional crystallization. Moreover, the chemical and mineralogical variation within the Craters suite also reflects control by crystal fractionation. The probability that contaminants

contributed significantly to the highly fractionated combination of elements that characterizes basic Craters lavas, and in sufficient quantity to effect the marked variation within the series, seems small. Indeed, the probability that such contamination occurred in at least three widely separated localities seems negligible. However, the extreme fractionation necessary for the development of these lavas probably required prolonged entrapment of magmas in comparatively shallow conduits, a situation conducive to wall-rock reaction which might have resulted in minor compositional changes such as addition of radiogenic strontium to the magma.

## References and Notes

1. M. Prinz, Bull. Geol. Soc. Amer. 81, 941 (1970).
2. I. C. Russell, U. S. Geol. Surv. Bull. 199 (1902), pp. 72-108.
3. \_\_\_\_\_, U. S. Geol. Surv. Bull. 217 (1903), pp. 38-47.
4. R. W. Limbert, Nat. Geog. Mag. 45, 303 (1924).
5. H. T. Stearns, Geog. Rev. 14, 362 (1924).
6. \_\_\_\_\_, Idaho Bur. Mines & Geol. Bull. 13 (1928), pp. 1-34.
7. \_\_\_\_\_, L. Crandall, and W. G. Steward, U. S. Geol. Surv. Wat.-Sup. Pap. 774 (1938), pp. 94-100.
8. J. G. Murtaugh, M.S. Thesis, Univ. of Idaho (1961).
9. E. Schulman and C. W. Ferguson, Jr., Appendix C in "Dendroclimatic Changes in Semiarid America", E. Schulman (Univ. of Arizona Press, Tucson, 1956), pp. 137-138. This "Triple Twist Tree" died in 1961.
10. H. T. Stearns, "Geology of Craters of the Moon National Monument, Idaho" (Craters of the Moon Natural History Association, Arco, 1963), p. 27.
11. F. M. Bullard and D. L. Rylander, Abs. Prog. Geol. Soc. Amer. 2, 273 (1970).
12. H. E. Malde and H. A. Powers, Bull. Geol. Soc. Amer. 73, 1197 (1962).
13. H. E. Malde, U. S. Geol. Surv. Prof. Pap. 644-F (in press).
14. \_\_\_\_\_, U. S. Geol. Surv. Prof. Pap. 596 (1968), pp. 10-11.
15. Russell referred to the region later named "Craters of the Moon" as "Cinder Buttes" (2, p. 72), so he entitled Hillebrand's data "Analysis of recent lava from the Cinder Buttes, Idaho" (2, p. 87). Stearns mistakenly surmised that Russell had collected the analyzed specimen from "the Big Cinder Butte flow" (6, p. 11), but Russell's descriptions (2, 3) clearly indicate that he thought it represented the lava stream now known as the North Crater pahoehoe flow (19). Slightly greater similarity to the analysis of sample 13 (Table 1) than to analyses of the North Crater flow (samples 7-9) suggests the possibility that Russell's sample may have come from the Big Craters northwest flow, which borders the North Crater flow on the west.
16. A. L. Anderson, Northwest Sci. 3, 17 (1929); \_\_\_\_\_, Idaho Bur. Mines & Geol. Pamph. 32 (1929), p. 20.
17. H. Williams' petrographic observations appear in Stearns et al. (7, p. 97).

18. G. T. Stone, Ph.D. Thesis, Univ. of Colorado (1967).
19. \_\_\_\_\_, Abs. Prog. Geol. Soc. Amer. Pt. 7, 217 (1969).
20. Nine of these analyses (samples 1, 5, 8-10, and 14-17) were previously presented as part of an oral paper (19), and four (samples 1, 8, 10, and 14) have recently been published with permission by C. E. Tilley and R. N. Thompson to support experimental data (86).
21. Sample collectors: 1, 8, 10, and 14, J. G. Murtaugh; 2 (and 11), R. M. Miller; 3 and 4, W. P. Leeman; 5, 9, 15, and 16, G. J. Neuerburg; 6 and 13, W. I. Manton; 7, C. J. Vitaliano; 17, H. A. Powers and G. T. Stone.
22. V. Manson, in "Basalts", H. H. Hess and A. Poldervaart, Eds. (Interscience, New York, 1967), vol. 1, p. 221. All but five of the more basic Craters of the Moon samples (1, 3, 4, 6, and 7) have crystallization index values [A. Poldervaart and A. B. Parker, Amer. J. Sci. 262, 281 (1964)] distinctly less than Manson's minimum for basalts (25.00 when  $\text{FeO} > 10\%$ ), and analyses 4, 9, and 13 do not meet his analysis-total criterion ( $99.00 < 101.00\%$ ). Although the diverse analyses of Table 1 vary slightly in accuracy, all are nevertheless useful in defining the chemical characteristics of the series.
23. \_\_\_\_\_, ibid., pp. 230-234.
24. G. A. MacDonald, Geol. Soc. Amer. Mem. 116 (1968), pp. 488-502.
25. D. L. Peck, T. L. Wright, and J. G. Moore, Bull. Volc. 29, 646 (1966); D. H. Richter and J. G. Moore, U. S. Geol. Surv. Prof. Pap. 537-B (1966), p. B20; L. R. Wager and G. M. Brown, "Layered Igneous Rocks" (Freeman, San Francisco, 1967), Fig. 115 and Pl. X; T. L. Wright and P. W. Weiblen, Prog. 1967 Ann. Mtgs. Geol. Soc. Amer., p. 243.
26. H. S. Yoder, Jr., and C. E. Tilley, J. Petrol. 3, 352 (1962).
27. C. E. Tilley, H. S. Yoder, Jr., and J. F. Schairer, Carnegie Inst. Wash. Year Book 64, 69 (1965).
28. S. R. Nockolds, Bull. Geol. Soc. Amer. 65, 1007 (1954).
29. R. A. Daly, "Igneous Rocks and the Depths of the Earth" (McGraw-Hill, New York, 1933), p. 470.
30. G. A. MacDonald and T. Katsura, J. Petrol. 5, 82 (1964).
31. M. A. Peacock, J. Geol. 39, 54 (1931).
32. L. R. Wager and G. M. Brown, "Layered Igneous Rocks" (Freeman, San Francisco, 1967), Fig. 115 and Pl. X.
33. H. Kuno, K. Yamasaki, C. Iida, and K. Nagashima, Jap. J. Geol. & Geog. 28, 179 (1957).

34. I. S. E. Carmichael, J. Petrol. 5, 435 (1964).
35. G. R. Robson and J. Spector, Nature 193, 1278 (1962).
36. A. C. Waters, Am. J. Sci. 259, 594 (1961).
37. H. Kuno, J. Petrol. 6, 306 (1965).
38. C. E. Tilley, H. S. Yoder, Jr., and J. F. Schairer, Carnegie Inst. Wash. Year Book 65, 260 (1967).
39. P. T. Robinson, Contr. Mineral. and Petrol. 22, 349 (1969).
40. B. M. Gunn and N. D. Watkins, Bull. Geol. Soc. Amer. 81, 1501 (1970).
41. K. G. Cox and R. MacDonald, Am. Mineral. 52, 1462 (1967).
42. D. L. Peck, T. L. Wright, and J. G. Moore, Bull. Volc. 29, 646 (1966).
43. H.-U. Schmincke, Bull. Geol. Soc. Amer. 78, 1410 (1967).
44. T. L. Wright and P. W. Weiblen, Prog. 1967 Ann. Mtgs. Geol. Soc. Amer. (1967), pp. 242-243.
45. R. B. Forbes and C. M. Hoskin, Science 166, 504 (1969).
46. H. E. Malde, H. A. Powers, and C. H. Marshall, U. S. Geol. Surv. Misc. Geol. Invest. Map I-373 (1963).
47. J. F. Evernden, D. E. Savage, G. H. Curtis, and G. T. James, Am. J. Sci. 262, 191 (1964).
48. H. A. Powers, U. S. Geol. Surv. Prof. Pap. 400-B (1960), p. B297.
49. G. R. Mansfield, U. S. Geol. Surv. Prof. Pap. 152 (1927).
50. \_\_\_\_\_, and E. S. Larsen, Wash. Acad. Sci. J. 5, 463 (1915).  
M. Prinz searched for but was unable to find the described locality.
51. A. L. Anderson and V. R. D. Kirkham [Am. J. Sci. 22 (5th ser.), 67 (1931)] suggested that the "nepheline basalt" might represent the extrusive equivalent of basic, potash-rich intrusive rocks at Caribou Mountain nearly 40 miles farther east.
52. W. Hamilton, U. S. Geol. Surv. Prof. Pap. 504-C (1965).
53. G. T. Stone, Geol. Soc. Amer. Sp. Pap. 87 (1965), p. 168.
54. W. J. Carr and D. E. Trimble, U. S. Geol. Surv. Bull. 1121-G (1963).
55. G. R. Mansfield, U. S. Geol. Surv. Bull. 713 (1920), p. 60.

56. Waldemar Lindgren contributed the first petrographic descriptions of basaltic lavas in the region of the Snake River Plain and used the designation "Snake River basalts" for the Pliocene and younger flows in the Plain and its tributary valleys: U. S. Geol. Surv. 18th Ann. Rept., Pt. 3 (1898), p. 626.
57. The samples of Table 2 were collected by M. Prinz and the analyses obtained by the late Arie Poldervaart.
58. A. T. Anderson and L. P. Greenland, *Geochim. Cosmochim. Acta* 33, 493 (1969).
59. W. I. Manton, 1966-1967 Ann. Rept. Geosci. Div. Southwest Cent. Adv. Studies (1967), pp. 30-31.
60. C. E. Hedge and F. G. Walthall, *Science* 140, 1214 (1963).
61. L. F. Rader, W. C. Swadley, H. H. Lipp, and C. Huffman, Jr., U. S. Geol. Surv. Prof. Pap. 400-B (1960), pp. B477-B480; L. F. Rader, W. C. Swadley, C. Huffman, Jr., and H. H. Lipp, *Geochim. Cosmochim. Acta* 27, 695 (1963).
62. A. J. Bartel, E. J. Fennelly, C. Huffman, Jr., and L. F. Rader, Jr., U. S. Geol. Surv. Prof. Pap. 475-B (1963), p. B23.
63. C. Patterson, G. Tilton, and M. Inghram, *Science* 121, 72 (1955).
64. R. G. Bates, U. S. Geol. Surv. Geophys. Inv. Map GP-446 (1964).
65. M. Prinz, in "Basalts", H. H. Hess and A. Poldervaart, Eds. (Interscience, New York, 1967), vol. 1, pp. 271-323.
66. T. G. Lovering, M. S. Niles, and M. L. Graves, U. S. Geol. Surv. Prof. Pap. 575-C (1967), p. C114.
67. R. A. Higazy, *Trans. Edin. Geol. Soc.* 15, 150 (1952).
68. L. R. Wager and R. L. Mitchell, *Geochim. Cosmochim. Acta* 3, 218 (1953).
69. S. R. Nockolds and R. Allen, *ibid.* 5, 245 (1954).
70. B. W. Evans, *ibid.* 28, 135 (1964).
71. A. Hietanen, U. S. Geol. Surv. Prof. Pap. 344-D (1963), p. D 30.
72. F. A. Frey, M. A. Haskin, J. A. Poetz, and L. A. Haskin, *J. Geophys. Res.* 73, 6085 (1968). "Olivine tholeiite" (D-3) from the East Pacific Rise has been reclassified as "andesite" (75). If the Jefferson County, Colorado, rock is from North or South Table Mesa, its classification as "basalt" is questionable.
73. The Lunar Sample Preliminary Examination Team, *Science* 167, 1325 (1970).
74. \_\_\_\_\_, *ibid.* 165, 1211 (1969).

75. L. A. Haskin, P. A. Helmke, and R. O. Allen, *ibid.* 167, 487 (1970).
76. B. R. Doe, *Quart. Colo. Sch. Mines* 63, 149 (1968).
77. W. I. Manton and W. P. Leeman, *Trans. Am. Geophys. Union* 50, 331 (1969).
78. W. P. Leeman and W. I. Manton, in preparation.
79. \_\_\_\_\_, *Trans. Am. Geophys. Union* 51, 444 (1970).
80. C. E. Hedge, *J. Geophys. Res.* 71, 6119 (1966).
81. I. S. E. Carmichael, *Contr. Mineral. and Petrol.* 14, 36 (1967).
82. Electron-probe data, G. T. Stone, in preparation.
83. A. Poldervaart and H. H. Hess, *J. Geol.* 59, 474 (1951).
84. R. N. Thompson and C. E. Tilley, *Earth and Planet. Sci. Lett.* 5, 471 (1969).
85. A. F. Buddington and D. H. Lindsley, *J. Petrol.* 5, 336 (1964).
86. C. E. Tilley and R. N. Thompson, *Earth and Planet. Sci. Lett.* 8, 79 (1970).
87. "T" and "G" are 59Pl3 and 59Pl3A (18); they probably are McKinney basalt of the Snake River Group (13).
88. J. H. Dover, *Geol. Soc. Amer. Sp. Pap.* 101 (1966), p. 301.
89. We thank the National Park Service for permission to collect rock samples in Craters of the Moon National Monument and W. I. Manton of the University of Texas at Dallas, R. M. Miller of Dearborn Community College, Dearborn, Michigan, and G. J. Neuerburg and H. A. Powers of the U. S. Geological Survey, Denver, Colorado, and Hawaii National Park, Hawaii, respectively, for permission to publish analyses of samples they collected (21).