

CRATERS OF THE MOON NM

Petrological and Mineralogical Variations in
2500–2000 yr B.P. Lava Flows, Craters of the Moon
Lava Field, Idaho*

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ABSTRACT

Basaltic lava flows were erupted 2500–2000 yr B.P. along the Great Rift volcanic rift zone at the Craters of the Moon lava field in the Snake River Plain volcanic province, Idaho. These flows form a diverse suite of rock types near the northern edge of the Snake River Plain but typical Snake River Plain basaltic flows were erupted nearly contemporaneously at the center of the plain. The Craters of the Moon lava flows range from basalt to trachyte, whereas rocks typical of the Snake River Plain are basalt and rhyolite with no intermediate types. The Craters of the Moon lava flows have chemical and mineralogical features that do not fit conveniently into any of several currently recommended rock classifications. Suggested names for the Craters of the Moon rocks, based on color index, SiO₂, P₂O₅, and TiO₂ contents, modal feldspar plus glass contents, Fe contents of olivine, and feldspar compositions, are basalt, trachybasalt, tristanite, and trachyte. Both the Craters of the Moon and Snake River Plain rocks are dominated by plagioclase and olivine and contain minor or lesser amounts of pyroxene. However, the Craters of the Moon rocks lack the Mg–Al and Cr-rich spinels and the Mg-rich olivines found in Snake River Plain basalts. Instead, the Craters of the Moon lava flows contain Fe-rich olivine, rare Fe-rich pyroxene, and minor alkali feldspar. Accessory minerals in the Craters of the Moon rocks are zircon and apatite. Chemical and mineralogical data, including Thompson space representations and mass balance calculations, suggest a genetic link between the Snake River Plain basalts and the Craters of the Moon lava flows. Thermodynamic modeling suggests that augite could appear on the liquidus of the Craters of the Moon lava flows at high pressures and including a more magnesian (earlier?) pyroxene in the fractionating assemblage improves the least-squares mass balance result. Processes of crystal fractionation and accumulation, overprinted by contamination by pumiceous rhyolite, can account for much of the diversity within the rock types from the Craters of the Moon lava field.

INTRODUCTION

The Snake River Plain volcanic province is aptly described by the quotation '...commonly, all volcanoes of a given "province" or area will erupt lavas which, although differing considerably, have persistent chemical characteristics that point to a common origin. How they originate and the reasons for their chemical diversity are among the most important questions of igneous petrology' (Verhoogen *et al.*, 1970). A distinctive characteristic of the Snake River Plain lava flows, chiefly basalts, is a limited range in chemical and mineralogical composition. They are typically low in silica and total alkalis, high in iron, and they crystallize olivine first, followed by plagioclase (Powers, 1960; Waters,

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1961; Stone, 1967; Jones, 1970; Leeman, 1974, 1982a, 1982b; Thompson, 1975; Stout & Nicholls, 1977). The province is dominated by olivine basalt and rhyolite; differentiated rocks are present only locally. One locality where differentiated rocks are a significant part of the volcanic pile is the Craters of the Moon lava field (Kuntz *et al.*, 1986a). Suggested petrologic interpretations that relate these rock types have been discussed by Kuntz *et al.* (1992).

This paper describes the chemical and mineralogical variations in a suite of basaltic and related rocks from Craters of the Moon (COM) lava field that formed during the youngest eruptive period, the 2500–2000 yr B.P. period A [terminology from Kuntz *et al.* (1986a)]. We present a data set for 22 rocks that represent most of the main lava flows of eruptive period A. This data set includes major-element analyses of the rocks and minerals, modal analyses, and distinctive petrographic features. We also suggest a possible nomenclature for the period A (COM-A) rocks and illustrate the differences and similarities between COM-A rocks and the olivine basalts of the Snake River Plain. Four samples have been selected to illustrate the COM-A rocks because they represent the variation in rock and mineral chemistry and in rock nomenclature. Accordingly, electron microprobe analyses of the minerals in only these four rocks are presented. However, the complete mineral-chemistry data set, gathered from microprobe analyses of minerals in all 22 COM-A samples, is illustrated in figures and available from the authors.

Snake River Plain

The Snake River Plain (SRP) is an arcuate structural and topographic depression of 600-km length and 50–100-km width in southern Idaho. The plain is bounded on the north by the Cretaceous plutonic rocks of the Idaho batholith and by block-faulted mountains that consist of folded Precambrian, Paleozoic, and Mesozoic rocks that were uplifted along NW-trending normal faults during Cenozoic basin-and-range tectonism. Similar block-fault mountains bound the plain along its southern margin. Tertiary rhyolitic and basaltic rocks of the Owyhee Plateau border the southwest side of the plain, and late Tertiary and Quaternary rhyolitic and basaltic rocks of the Yellowstone Plateau are at the northeast end of the plain (Fig. 1).

The western SRP is a late Neogene, fault-bounded graben containing basalt and rhyolite lava flows and thick, interbedded detrital sediments (Malde & Powers, 1962; Malde, 1991). The eastern SRP is a broad, flat, lava plain consisting of mostly Pleistocene and Holocene basaltic lava flows and thin, interbedded sediments (Malde, 1991; Kuntz *et al.*, 1992). Most lava fields of the SRP province represent monogenetic eruptions from vents that are widely scattered in both space and time. The three latest Pleistocene to Holocene lava fields, Craters of the Moon, Kings Bowl, and Wapi, are located along the Great Rift, a volcanic rift zone of 85-km length and 2–8-km width (Fig. 2, Kuntz *et al.*, 1988).

Craters of the Moon Lava Field

The Craters of the Moon (COM) lava field contrasts with other lava fields in the SRP because it is a composite, polygenetic field composed of at least 60 flows erupted from 25 tephra cones and at least 8 eruptive-fissure systems. The COM field is the largest, dominantly Holocene lava field in the conterminous USA; it covers ~1600 km² and contains ~30 km³ of lava flows, and associated vent and pyroclastic deposits. Stratigraphic relationships, paleomagnetic studies, and radiocarbon ages (Kuntz *et al.*, 1986b) show that the COM field formed during eight eruptive periods, designated as H, oldest, to A, youngest. The first eruptive period (H) began ~15 000 yr B.P. and the latest eruptive period (A) began ~2500 yr B.P. and ended ~2000 yr B.P. (Kuntz *et al.*, 1986a).

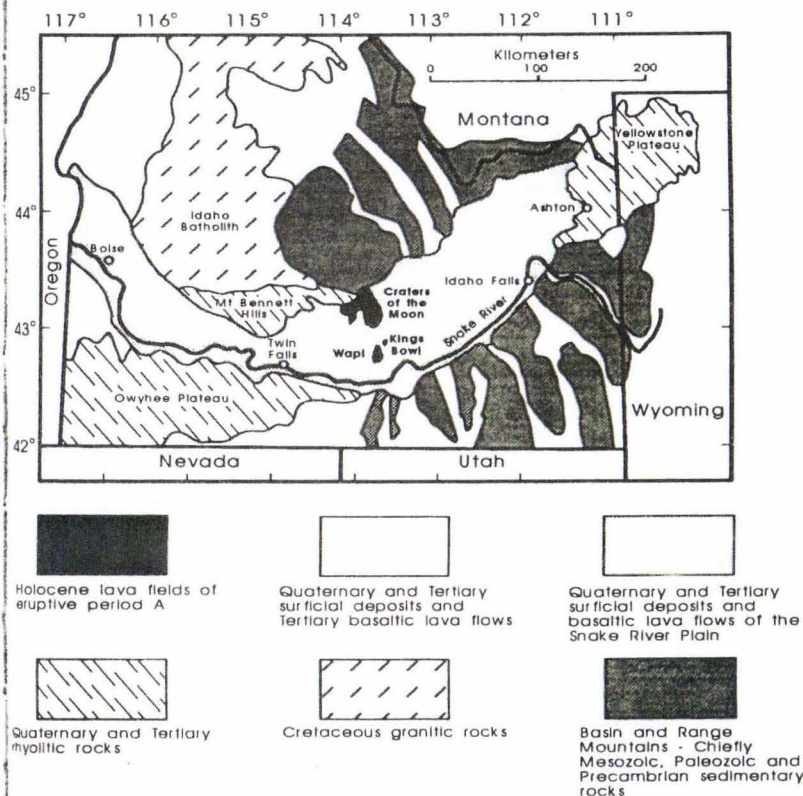


Fig. 1 Map showing the location of 2500–2000 yr B.P. lava fields (Craters of the Moon, Kings Bowl, and Wapi) within the Snake River Plain, Idaho.

Lava flows of the COM field have a broad range in chemical composition; the broadest range (46.6–63.5% SiO₂) is in flows from eruptive period A (Kuntz *et al.*, 1986a). The stratigraphic order of major lava flows, radiocarbon ages, lava types of major flows, and source vents for eruptive period A are listed in Table 1 and shown in Fig. 2. The flows or flow sequences of the period A-COM lava field and field numbers of the 22 chosen samples are listed in Table 2. The Kings Bowl and Wapi lava fields, along the southern part of the Great Rift volcanic zone, are approximately coeval with the COM-A flows along the northern part of the Great Rift volcanic zone (Fig. 2), but the Kings Bowl and Wapi lava fields consist of olivine basalt flows that are similar to the olivine basalts covering the vast part of the SRP.

Analytical Methods

Modes of COM-A rocks were determined by automatic counting on the electron microprobe, thus eliminating the Holmes effect (Chayes, 1956, Chapter 11) and allowing the identification of small

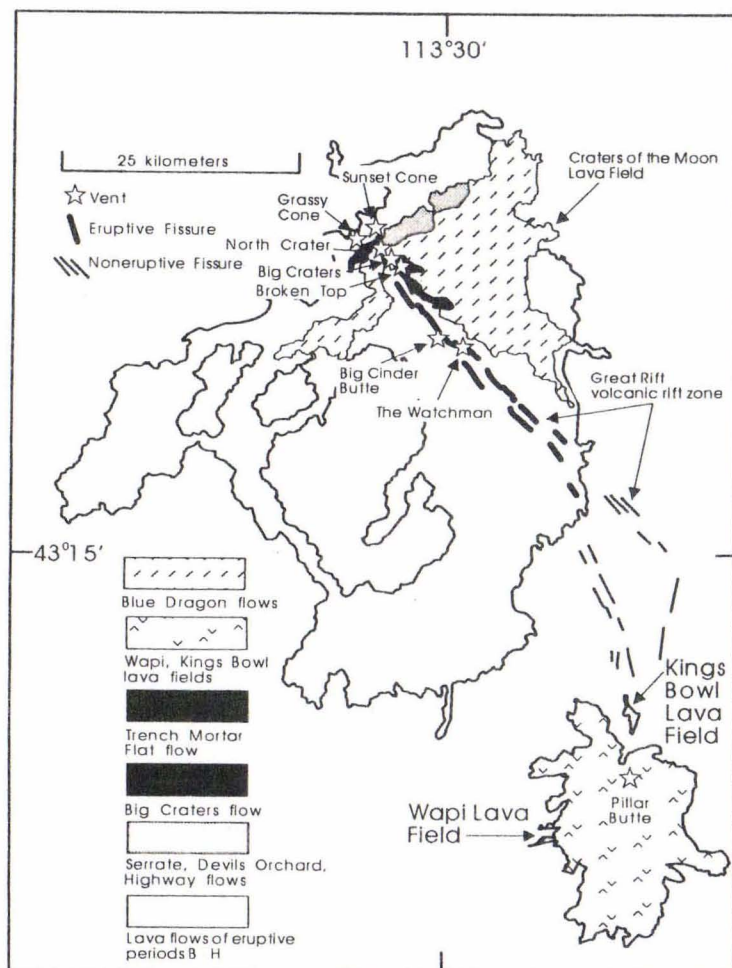


FIG. 2. Map of Craters of the Moon, Kings Bowl, and Wapi lava fields along the Great Rift volcanic rift zone.

crystals that are often difficult to identify by optical methods. One-second counts on Ca, K, Na, Ti, Si, Al, Fe, and Mg were ranked and compared with the ranking expected for the minerals in these rocks, i.e., standard lines (Nicholls & Stout, 1986). Counting was done on a 200- μ m grid spacing, and an average of 5000 spots were analyzed per sample. Approximately 75% of the analyzed spots in each sampler were identified as specific minerals or as glass. The modes were normalized to 100% excluding the unidentified spots.

Rocks were analyzed by combined X-ray fluorescence and chemical methods [Kuntz et al., 1985;

TABLE 1

Ages, informal names, and source vents for lava flows of period A, Craters of the Moon, Kings Bowl, and Wapi lava fields, Snake River Plain, Idaho (Kuntz et al., 1986a, 1986b)

Radiocarbon age (yr)	Informal name of major flows	Source vents (quoted where uncertain)
n.d.	Broken Top	Eruptive fissures, east and south flanks of Broken Top cinder cone
2076 $\pm$ 45	Blue Dragon	Eruptive fissures south of Big Craters cinder cone complex
2205 $\pm$ 25	Trench Mortar Flat	Eruptive fissures between Big Cinder Butte and The Watchman cinder cones
n.d.	North Crater	North Crater cinder cone
2400 $\pm$ 300	Big Craters (Green Dragon)	Eruptive fissure at north end of Big Craters cinder cone
n.d.	Serrate	North Crater cinder cone (?)
n.d.	Devils Orchard	North Crater cinder cone (?)
n.d.	Highway	North Crater cinder cone (?) or tholoid vent (?) between Grassy Cone and Sunset Cone cinder cones
2222 $\pm$ 100	Kings Bowl	Fissure vents north and south of Kings Bowl
2270 $\pm$ 50	Wapi	Vents at Pillar Butte

and references therein]. Analytical methods used for a Devils Orchard rock (DO2, Table 2) have been given by Leeman et al. (1976). Analyses are listed in Table 3.

Minerals and glasses were analyzed with an Applied Research Laboratories SEMQ 8-channel wavelength dispersive electron microprobe. Eight elements were determined simultaneously under the following operating conditions: take-off angle, 52.5°; accelerating voltage, 15 kV; emission current, 300 nA; beam current, 0.15 mA on minerals and 0.05 mA on glass; beam diameter < 1 μ m (size of amnescent spot on plagioclase); counting time, 20 s on minerals, 40 s on glass. Correction procedures, estimates of precision and detection limits have been described by Nicholls & Stout (1988, pp. 1056-7).

CLASSIFICATION

COM-A rocks do not fit conveniently into currently recommended rock classifications. For example, the most MgO-rich, SiO₂-poor COM-A rock is basalt in the IUGS modal classification (Streckeisen, 1979), alkali basalt according to Irvine & Baragar (1971), trachybasalt in the IUGS chemical classification (La Bas et al., 1986), and andesite in the normative IUGS classification (Streckeisen, 1979). The extensive basalt flows of the SRP are less problematic; they have been called olivine tholeiitic basalts (Leeman, 1975), alkali olivine basalts (Stout & Nicholls, 1977) or simply olivine basalts (Kuntz et al., 1986a). This variation in basalt names reflects the different criteria used to classify rocks, normative vs. modal mineralogy, rather than any fundamental disagreement about the composition of the SRP basalts. That they are olivine basalts is not in doubt.

The glass contents of the COM-A rocks renders assigning names based on modal mineralogy difficult. In an attempt to overcome this problem, the modes were normalized glass free to provide an estimate of color index that is independent of glass content (Table 4). This assumes that glass would crystallize to a mineral assemblage of phases in the same proportions as identified crystals in the rock. The presence of only a few phenocrysts (< 1%

TABLE 2

Flow sequences and field numbers of samples referred to in text, figures, and other tables [Kuntz et al. (1985), excluding samples marked with an asterisk]; rock types are those discussed in text

Flow or flow sequence	Field no.	Label in text	Rock type
Broken Top flow	79K89	BT1	Olivine basalt
	78K12	BT2	Trachybasalt
	78K13	BT3	Trachybasalt
Blue Dragon flows	78K52	BD1	Trachybasalt
	79K106	BD2	Trachybasalt
Trench Mortar Flat flow	78K46	TMF1	Trachybasalt
	78K126	TMF2	Trachybasalt
	78K43B*	TMF3	Trachybasalt
	78K42A*	TMF4	Trachybasalt
North Crater flow	79K90*	NC1	Trachybasalt
	78K122*	NC2	Trachybasalt
Big Crater flows	79K12	BC1	Trachybasalt
	78K19	BC2	Trachybasalt
	78K120	BC3	Trachybasalt
Serrate flow	78K121	Se1	Tristanite
	78K99	Se2	Trachyte
	79K93	Se3	Trachyte
Devils Orchard flow	DO-1	DO1	Tristanite
	78K182	DO2	Trachyte
Highway flow	78K151*	Hy1	Tristanite
	78K152	Hy2	Trachyte
	78K4*	Hy3	Trachyte

by volume) in these rocks suggests that the glass compositions are similar to the groundmass-dominated, whole-rock compositions. The more mafic rocks have estimated color indices > 20, whereas the more felsic rocks have estimated color indices < 10. Only three of the 22 rocks (Se1, DO1, and Hy1) have estimated color indices between 10 and 20.

The four samples selected to represent the variation in the COM-A rock types are: (1) Broken Top flow, BT1, which is the most primitive rock in this study and has the lowest SiO₂ and highest MgO contents; (2) a less primitive Broken Top flow, BT2; (3) Serrate flow, Se1, and (4) Serrate flow, Se2, representing the least primitive rocks. The rock names derived from the widely used classification developed by Irvine & Baragar (1971), the IUGS recommended chemical classification (Le Bas et al., 1986), and the IUGS recommended modal and normative classifications (Streckeisen, 1979) are illustrated and summarized in Fig. 3.

All these methods classify more than one of the four selected rocks as the same type. To complicate the process further, in three classifications the duplicated names do not apply to the same rocks. In the IUGS normative classification (Fig. 3c), all four rocks have the same name even though the rock and mineral chemistry of each of these rocks are distinctly different. To facilitate description and discussion of the chemical and mineralogical characteristics of the 22 rocks in this study (Table 2), it is necessary to identify similar rocks as the same rock type.

We distinguish the four rocks selected to represent the variation in rock types as basalt, the most primitive rock, trachybasalt and tristanite, as intermediate rock types, and trachyte as

TABLE 3

Chemical analyses of the Craters of the Moon, period A lava flows [Kuntz et al., (1985), except HY1, unpublished analysis]

	BT1	BT2	BT3	BD1	BD2	TMF1	TMF2	BC1	BC2
SiO ₂	47.81	50.49	50.89	49.01	49.61	49.79	51.08	51.26	51.55
TiO ₂	3.20	2.64	2.67	2.87	2.75	2.91	2.57	2.51	2.55
Al ₂ O ₃	13.59	13.12	14.22	13.41	13.82	13.65	13.29	14.22	14.37
Fe ₂ O ₃	1.17	1.86	3.12	0.77	2.32	1.15	1.72	1.35	1.96
FeO	14.62	13.07	12.05	14.50	12.97	13.43	12.16	13.28	12.77
MnO	0.26	0.24	0.24	0.24	0.25	0.24	0.23	0.25	0.24
MgO	3.97	2.91	2.83	3.34	3.25	3.65	3.05	2.90	2.82
CaO	7.31	6.97	7.03	6.93	6.56	7.59	6.82	6.37	6.79
Na ₂ O	3.45	3.44	3.43	3.61	3.47	3.28	3.55	3.58	3.52
K ₂ O	1.80	2.19	2.18	2.03	2.05	2.05	2.39	2.18	2.26
P ₂ O ₅	2.36	1.77	1.60	1.77	1.88	1.84	1.44	1.63	1.48
H ₂ O ⁺	0.18	0.13	0.03	0.20	0.41	0.27	0.13	0.33	0.18
H ₂ O	0.04	0.10	0.04	0.14	0.10	0.12	0.06	0.09	0.12
CO ₂	0.11	0.04	0.03	0.10	0.11	0.05	0.02	0.09	0.04
Total	99.87	98.97	100.36	98.92	99.55	100.02	98.51	100.04	100.65
	BC3	Se1	Se2	Se3	DO1	DO2	Hy1	Hy2	
SiO ₂	52.04	54.51	59.91	61.55	56.75	62.60	54.70	62.88	
TiO ₂	2.54	1.82	0.95	0.68	1.29	0.73	1.70	0.67	
Al ₂ O ₃	13.91	13.84	13.94	14.42	14.51	14.80	13.80	14.49	
Fe ₂ O ₃	1.33	1.56	2.94	0.78	2.39	1.79	15.40	0.88	
FeO	13.40	11.81	7.44	7.62	10.63	7.45	n.d.	7.58	
MnO	0.24	0.21	0.18	0.18	0.25	0.20	0.26	0.17	
MgO	2.68	1.82	0.52	0.36	1.12	0.35	1.67	0.27	
CaO	6.76	5.25	3.55	3.02	4.56	3.19	5.05	2.94	
Na ₂ O	3.57	3.78	4.00	3.80	4.02	4.05	3.80	4.20	
K ₂ O	2.31	2.87	3.91	4.52	3.32	4.67	2.97	4.64	
P ₂ O ₅	1.47	1.03	0.29	0.19	0.63	0.19	1.01	0.14	
H ₂ O ⁺	0.18	0.28	0.11	0.30	0.15	0.18	<0.01	0.14	
H ₂ O	0.03	0.05	<0.01	0.10	0.03	0.01	<0.01	0.03	
CO ₂	0.04	0.02	0.01	0.08	0.01	0.06	<0.01	0.02	
Total	100.50	98.85	97.75	97.60	99.66	100.27	100.36	99.05	

the least primitive rock (Table 2). We suggest that these predominantly fine-grained, glassy rocks are best described by a classification based on their whole-rock chemistry, by the amounts of feldspar and glass, and by the composition of the dominant mineral phase, feldspar.

CHEMISTRY

The COM-A lava flows show distinctive characteristics that are common to the SRP volcanic province in terms of whole-rock and mineral chemistry. They also have features that are present only in the COM-A lava flows. These distinctive features are due in part to the different rock types found at COM compared with the rest of the SRP. Common and contrasting characteristics are illustrated in the following sections.

The SiO₂ contents of 52 COM-A rocks span two ranges, ~46–52 wt.% and ~55–64 wt.% [table 2 of Kuntz et al. (1985); see also Fig. 4a]. The hiatus between the two ranges marks the break between basalt trachybasalt and tristanite trachyte. Si/K ratios also show a compositional hiatus between the two groups. The basalts and trachybasalts have ratios in the range 17–21 whereas the tristanites and trachytes have ratios in the range 9–15. None of

TABLE 4

Modes (vol. %) of the Craters of the Moon, period A lavas, determined by electron microprobe

Sample	Oliv	Pyx	Esp	Ap	Op	Glass	Esp + Gls	CI
BT1	12.83	0.06	40.43	5.83	4.35	36.50	76.93	36.33
BT2	9.39	2.02	49.72	5.06	6.79	27.02	76.74	31.87
BT3	9.88	7.23	42.81	4.77	6.60	28.70	71.51	39.95
BD1	13.61	0.06	60.17	5.53	4.14	16.49	76.66	27.95
BD2	10.25	6.68	46.61	3.79	6.11	26.56	73.17	36.53
TMF1	10.48	3.99	67.17	2.45	5.94	9.98	77.15	25.39
TMF2	6.04	4.53	55.06	2.57	5.91	25.88	80.94	25.71
TMF3	7.55	3.22	49.52	1.79	6.76	31.16	80.68	28.07
TMF4	15.18	3.16	53.74	6.68	7.16	14.08	67.82	37.45
NC1	9.30	0.03	52.97	2.04	3.43	32.23	85.20	21.84
NC2	12.83	0.57	65.14	3.74	4.46	13.27	78.41	24.90
BC1	12.07	0.55	62.48	3.57	4.58	16.75	79.23	24.95
BC2	8.77	5.00	49.39	4.06	7.03	25.75	75.14	33.48
BC3	7.74	0.12	60.29	2.81	4.62	24.42	84.71	20.23
Se1	7.57	0.40	68.55	1.94	2.65	18.89	87.44	15.49
Se2	1.78	2.21	85.24	0.25	3.48	7.03	92.27	8.30
Se3	2.27	0.45	74.19	0.18	0.90	22.02	96.21	4.87
DO1	3.58	2.29	65.55	0.77	2.55	25.26	90.81	12.30
DO2	2.04	0.74	31.33	0.06	0.46	65.38	96.71	9.53
Hy1	8.19	1.79	80.74	1.69	3.19	4.41	85.15	15.54
Hy2	1.49	0.58	69.91	0.11	1.21	26.69	96.60	4.62
Hy3	4.10	1.11	69.52	0.52	0.52	24.22	93.74	8.25

Oliv, olivine; Pyx, pyroxene; Esp, feldspar; Ap, apatite; Op, opaques; Gls, glass; CI, Color index, calculated after normalizing to glass free.

the 52 available analyses have SiO_2 contents or Si/K values between the ranges cited. In contrast, SRP olivine basalts have SiO_2 contents between 46 and 49 wt. % and SRP rhyolites have SiO_2 contents between 68 and 75 wt. % (Fig. 4a). The corresponding Si/K values are 40.88 and 9.12. We use Kings Bowl basalt flows as a basis for comparing COM-A flows with SRP olivine basalts because the Kings Bowl basalts have the chemical and mineralogical characteristics of SRP olivine basalts, are roughly contemporaneous with the COM-A flows (Kings Bowl erupted at 2222 ± 100 B.P.; Kuntz *et al.*, 1986b), and were erupted just south of the COM lava field along the Great Rift volcanic rift zone (Fig. 2).

The increase in SiO_2 content in the COM-A lava flows is accompanied by a continuous drop in wt. % P_2O_5 , MgO , and TiO_2 , and an increase in K_2O . Distinct breaks in the abundances of these oxides occur at changes in rock type (Table 3). Figure 4b illustrates the value of these oxides for all 17 analyzed rocks. Solid circles mark the four representative rocks.

The Kings Bowl olivine basalts have SiO_2 contents comparable with those in the COM-A basalt and trachybasalts but have consistently lower concentrations of P_2O_5 and K_2O , lower to equal contents of TiO_2 , and more than twice the concentration of MgO (Fig. 4b).

Thompson space representation of rock compositions

A summary of the chemical variations in COM-A lava flows and the differences between SRP basalts and COM-A rocks can be illustrated on a Thompson space diagram (Thompson, 1982a, 1982b). A Thompson space representation of a rock analysis is similar to a CIPW normative representation but has attributes not possessed by the norm. The modal amount of a mineral phase can be directly related to its Thompson space representation; the

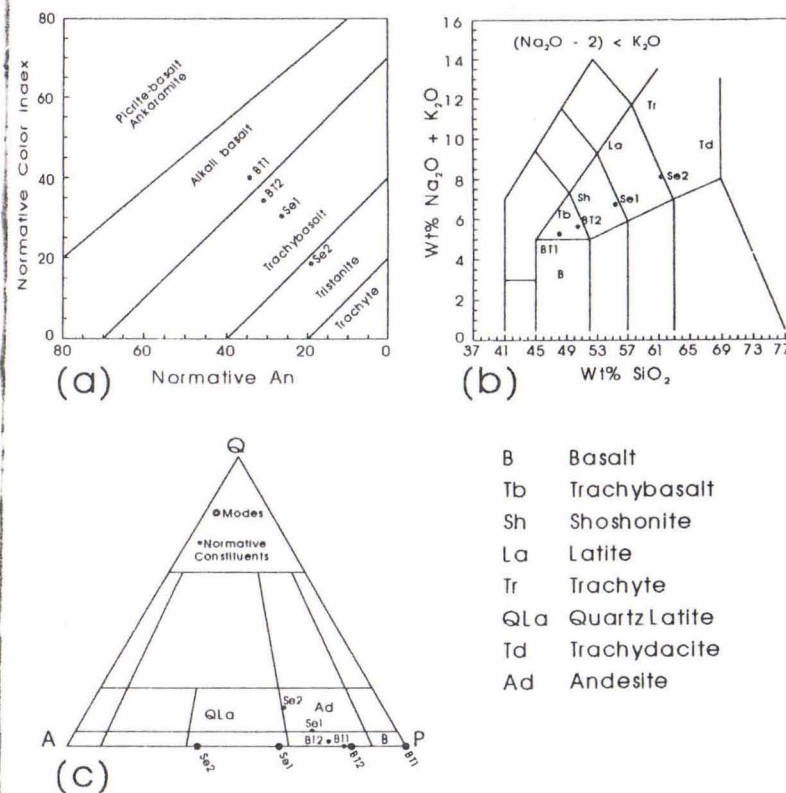


FIG. 3. Rock names in (a) the Irvine & Baragar (1971) classification, (b) the total alkalis vs. SiO_2 (TAS) classification (Irvine & Baragar, 1971), (c) the IUGS quartz, alkali feldspar, plagioclase classification with normative components (QAPF Normative; Streckeisen, 1979), and the IUGS recommended modal classification. Q, quartz; P, plagioclase; A, alkali feldspar.

Thompson space representation can be tailored to the mineral assemblage and to the mineral compositions of a particular rock or rock suite, in this instance, plagioclase, olivine, pyroxene, and quartz or melt (glass); and the Thompson space representation can be graphically displayed and visualized.

The essential feature of Thompson space representations of rocks and minerals is that the

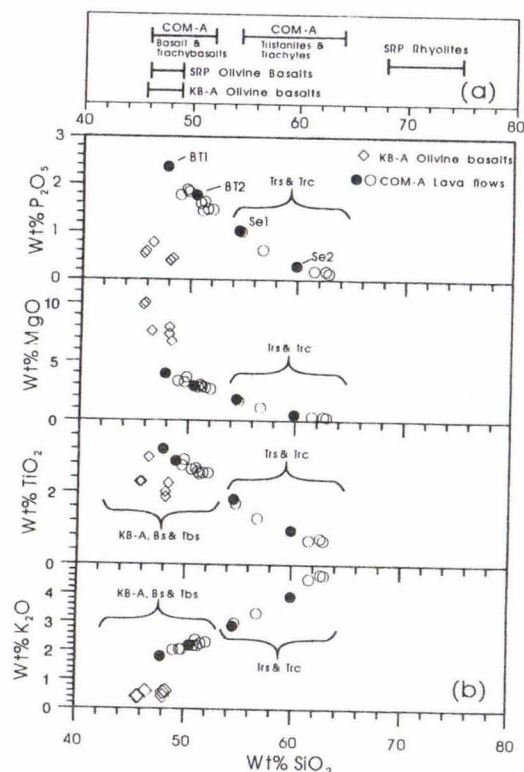


FIG. 4. (a) SiO_2 range and rock types in COM-A lava flows, Kings Bowl olivine basalts (KB-A), and Snake River Plain olivine basalts (SRP). (b) P_2O_5 , MgO , TiO_2 , and K_2O variations with SiO_2 content in COM-A lava flows. Bt basalt; Tbs, trachybasalt; Trs, tristanite; Trc, trachyte.

amount of a potential or actual phase in a rock is represented by an additive component and the compositions of the phases are represented by exchange components. Any conventional end-member can be chosen as the additive component of a phase. For example, an additive component for pyroxenes could be $\text{CaMgSi}_2\text{O}_6$. If the transformation of the rock analysis produces 1 mole of $\text{CaMgSi}_2\text{O}_6$ in the set of Thompson components than the modal amount of pyroxene expected in the rock is 1 mole. A possible exchange component might be FeMg_{-1} , a formula that represents the Fe-Mg exchange in minerals. If the transformed analysis of a pyroxene shows this component to be 0.5, then the composition of the pyroxene would be $\text{Di}_{0.5}$. Rather than write out $\text{CaMgSi}_2\text{O}_6$ and FeMg_{-1} , symbols are used. Exchange components are written in italics. The symbols and names of the components used in this paper are listed in Table 5.

The amount of a component that is available for the transformation of one mineral assemblage to another limits the extent of Thompson space available to a rock composition.

TABLE 5
Symbols for Thompson space components

Symbol	Name	Formula	Phase
<i>Additive component</i>			
Di	Diopside	$\text{CaMgSi}_2\text{O}_6$	Pyroxene
An	Anorthite	$\text{CaAl}_2\text{Si}_2\text{O}_8$	Feldspar
For	Forsterite	Mg_2SiO_4	Olivine
Sp	Spinel	MgAl_2O_4	Fe-Ti Spinel
Q	Quartz	SiO_2	Quartz, melt
<i>Exchange component</i>			
tk	Tschermaks	$\text{Al}_2\text{Mg}_{-1}\text{Si}_1$	
pl	Plagioclase	$\text{NaSiCa}_{-1}\text{Al}_1$	
ed	Edenite	NaAlSi_{-1}	
mc		MgCa_{-1}	
fm		FeMg_{-1}	

For example, an initial assemblage containing plagioclase, represented by An, can transform under changing conditions of P and T to an assemblage containing pyroxene and quartz:

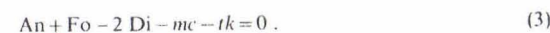


The maximum extent to which this transformation can proceed is limited by the initial amount of An. One unit of displacement in the positive direction corresponds to the transformation of 1 mole of An, plagioclase, into 1 mole of Di, pyroxene, 1 mole of Q and 1 mole of tk. The extent of such transformations can be treated as vectors and plotted on orthogonal axes.

A convenient starting point for calculating the relevant Thompson space for an igneous rock is to transform the rock analysis into two additive components, An and Di, plus the necessary exchange components (Nicholls *et al.*, 1991). Because the COM-A rocks contain modal olivine and all but two are quartz-normative, the axes chosen to represent a Thompson space for these rocks should include transformations to mineral assemblages containing these two minerals. Two convenient transformations are



and



The corresponding Thompson space representation of the four COM-A rocks and the youngest Kings Bowl basalt is shown in Fig. 5. There are several features of this diagram to note:

(1) The diagram is for crystalline assemblages consisting of olivine, plagioclase, pyroxene, and quartz in some combination.

(2) Ulvöspinel-magnetite solid solutions are not represented on the diagram. They could be taken into account by making the space three-dimensional with a transformation such as



Because the amount of a phase is represented by the additive component, the amount of Fe-Ti oxide is represented by Sp. The composition of the oxide is determined by the exchange components. A spinel with the composition of ulvöspinel (Fe_2TiO_4) would be represented by

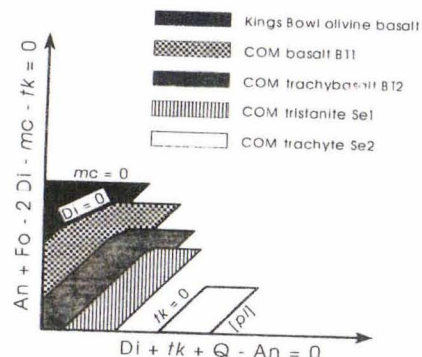


Fig. 5. Thompson space diagram for the Craters of the Moon lava flows and a Kings Bowl olivine basalt.



Exchange components do not alter the amount of the phase, represented by MgAl_2O_4 , only its composition. The amount of Fe-Ti spinel in these rocks is small (see Table 4); consequently, displacement along the third axis is also small and the effective Thompson spaces will be little displaced from those shown in Fig. 5.

(3) The symbol $[pl]$ in Fig. 5 represents the constraint:



Unless the pyroxenes contain significant amounts of Na, the only phase in the assemblage plagioclase, pyroxene, olivine, quartz, and spinel that can contain Na is plagioclase. The pyroxenes in these rocks, besides being sparse, contain very little Na (see Table 7 below). Consequently, in a solid assemblage, the $[pl]$ line is a limit on the reaction space.

(4) The boundaries of the Thompson space are lines where an exchange component is zero or constrained ($mc=0$, $tk=0$, or $\text{An}=pl$) or where an additive component is zero (the x -axis where $\text{Fo}=0$, the y -axis where $Q=0$ and the line $\text{Di}=0$). COM basalt, trachybasalts and tristanites have a boundary where it is possible to have an assemblage without pyroxene (i.e., where $\text{Di}=0$). The trachytes and the Kings Bowl basalt cannot produce assemblages that lack pyroxene if components that represent the observed phases in the rocks are used to form the Thompson space polygon.

The positions of the Thompson spaces on the axes, the lack of a $\text{Di}=0$ boundary in some rock compositions, and the extent of that boundary, where present, all illustrate the chemical mineralogical differences among these rocks. Spaces available to each rock composition overlap for the more SiO_2 -poor compositions, but the most felsic and SiO_2 -rich rock has a distinct compositional space. The Thompson space diagram also suggests that there is a progressive change in composition from basalts in the SRP to COM-A lava flows. The implied genetic relationship between SRP and COM-A lava flows and among COM-A lava flows, based on chemistry, may be further defined and constrained by the mineral compositions, modal abundances, and petrographic features of the COM-A rocks.

MODES

Olivine and plagioclase are the dominant and largest mineral phases in basaltic rocks from the SRP province (Stone, 1967; Leeman, 1974; Stout & Nicholls, 1977). Megacrysts and

phenocrysts of pyroxene, Fe-Ti oxides, and apatite are much less common. This is also true of the COM-A basalt and trachybasalts. However, in the trachytes large crystals of pyroxene, Fe-Ti oxides, and apatite are nearly as common as olivine and feldspar. Like many other rocks in the SRP volcanic province, the COM-A rocks carry few phenocrysts and groundmass textures vary from nearly holocrystalline to glassy. The COM-A flows are typically more glassy than SRP flows; most contain >20% glass and one, a Devils Orchard flow, contains 65% glass (DO2, Table 4).

The high TiO_2 and FeO contents are reflected in the high modal abundance of Fe-Ti oxides in SRP basalts and in COM-A basalts and trachybasalts (Fig. 6, Table 4). Magnetite

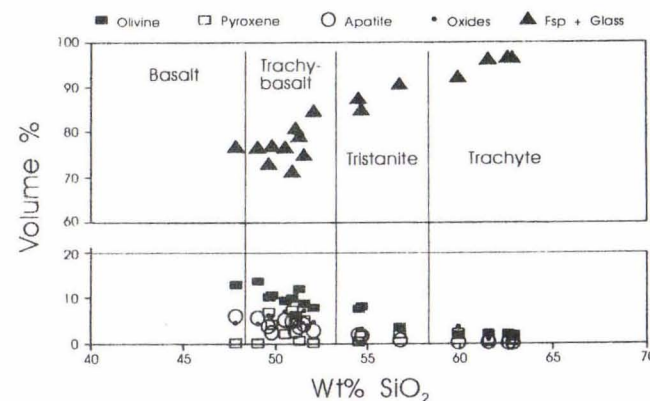


Fig. 6. Modal amounts of minerals vs. wt.% SiO_2 for the COM-A rocks listed in Table 3.

is the dominant oxide whereas ilmenite is subordinate. Ilmenite is just detectable in seven rocks and is absent in two others. Only two trachybasalts, Trench Mortar Flat flows, have substantial amounts (>2%) of ilmenite, although ilmenite is generally present in substantial amounts in SRP olivine basalts (Thompson, 1973; Stout & Nicholls, 1977). Most of the trachyte flows have small amounts of modal Fe-Ti oxides and only one (Se2) has ilmenite, a megacryst, which coexists with a magnetite megacryst.

Abundant apatite reflects the high P_2O_5 contents in the basalt and trachybasalt (Table 4). Apatite is primarily a groundmass phase in these rocks, but some occurs as microphenocrysts (<500 μm in largest dimension). Apatite is markedly less abundant in the low- P_2O_5 -bearing tristanites (<2%) and trachytes (from <1% to ~0.1%) although trachytes contain large apatite crystals in glomerocrysts.

The low abundance of pyroxene, equal to or less than apatite in COM-A lava flows, is also a common feature in SRP olivine basalts. Eleven of the 22 COM-A rocks analyzed have <1% pyroxene and only three rocks have $\geq 5\%$. Pyroxene does not occur as a phenocryst in any of the COM-A rocks, although there are rare microphenocrysts in one tristanite, DO1. Pyroxene occurs only in the groundmass of the basalt and trachybasalts but is present in glomerocrysts with olivine, magnetite, and apatite in trachytes. Like SRP basalts, modal low-calcium pyroxene is rare to nonexistent in COM-A rocks. It is found as very small

crystals in the groundmass of only six of the 22 rocks (BD2, TMF3, BC2, BC3, Se1, and Hy1).

PETROGRAPHY

Compared with SRP olivine basalts, the COM-A rocks have several distinct petrographic features, including the following:

(1) Glomerocrysts of large (up to 1.5 mm), Fe-rich olivine ($\sim \text{Fa}_{84}\text{-Fa}_{92}$), Fe-rich pyroxene ($\sim \text{Fs}_{41}\text{-Fs}_{55}$), magnetite, and apatite occur in trachytes. Some olivine and pyroxene crystals in the glomerocrysts have pronounced reaction rims but many do not (Fig. 7).

(2) The glomerocrysts are typically accompanied by small, euhedral cubes of zircon in embayments or attached to mineral edges (Fig. 7a and b).

(3) Tristanites and trachytes contain large (up to 2.5 mm) megacrysts of plagioclase and/or alkali feldspar (Fig. 7c). Plagioclase megacrysts also occur in several trachybasalts but alkali feldspar does not. Typically, feldspar megacrysts have corroded centres and reaction rims ranging from ~ 5 to $\sim 25 \mu\text{m}$ width and, like the glomerocrysts, are commonly accompanied by small zircon crystals (Fig. 7c).

(4) Abundant alkali feldspar (anorthoclase and sanidine) in the groundmass of tristanites and trachytes has a high celsian component (up to 5.1 mol% in a Devils Orchard flow, DO2).

Inclusions of pumiceous rhyolite, ranging from microscopic to meter-size fragments, occur at several cinder cones that are possible source vents for period A trachyte flows (Kuntz *et al.*, 1992). Microscopic pumice inclusions are common in some trachytes and meter-size pumice inclusions have been recognized in these flows. Geophysical evidence is consistent with the suggestion that the inclusions represent Tertiary rhyolitic rocks that form the upper crust through which the magmas rose to the surface (Embree *et al.*, 1982; Mabey, 1982).

Microscopic pumice inclusions examined in this study (79K25, 78K157B, and 78K159 from North Crater flows) consist almost entirely of feldspar, glass, and quartz. The feldspar is dominantly alkali feldspar, but one inclusion, a volcanic breccia (78K159), also carries plagioclase phenocrysts as calcic as An_{50} . Minor titanite occurs in some of these inclusions.

Two granulite xenoliths (78K34 and 78K158) have schistose to gneissic textures. One (78K34) in a Devils Orchard flow has the mineral assemblage of granulite-facies rocks: orthopyroxene, clinopyroxene, quartz, and plagioclase ($\sim \text{An}_{20}\text{-An}_{30}$). The other xenolith (78K158) is similar, but contains biotite and lacks clinopyroxene. Both xenoliths are altered. Accessory minerals include zircon, baddelyite (in 78K34) and opaque minerals. Attached to 78K34 is a fragment of a glassy vesicular lava flow having groundmass plagioclase laths aligned in a trachytic texture. This glassy rock also includes a megacrystic and/or glomerocrystic assemblage similar to a glomerocrystic assemblage in the Devils Orchard trachyte (DO2): both assemblages contain pyroxene, Fe-Ti oxides, plagioclase with reaction rims, and zircon. However, olivine is also part of the assemblage in the Devils Orchard trachyte, but no megacrystic or glomerocrystic olivine is in the glassy rock attached to the xenolith 78K34.

Leeman *et al.* (1976) reported xenoliths of crustal rocks in several other COM-A lava flows. Although xenoliths of Precambrian gneiss have been found in SRP olivine basalt (see, e.g., Leeman *et al.*, 1985), these xenoliths are very rare outside the Craters of the Moon area (Kuntz *et al.*, 1992).

No textural differences related to rock type were observed in the groundmass of COM-A rocks. Typically, glass encloses groundmass olivine, opaque minerals, and randomly

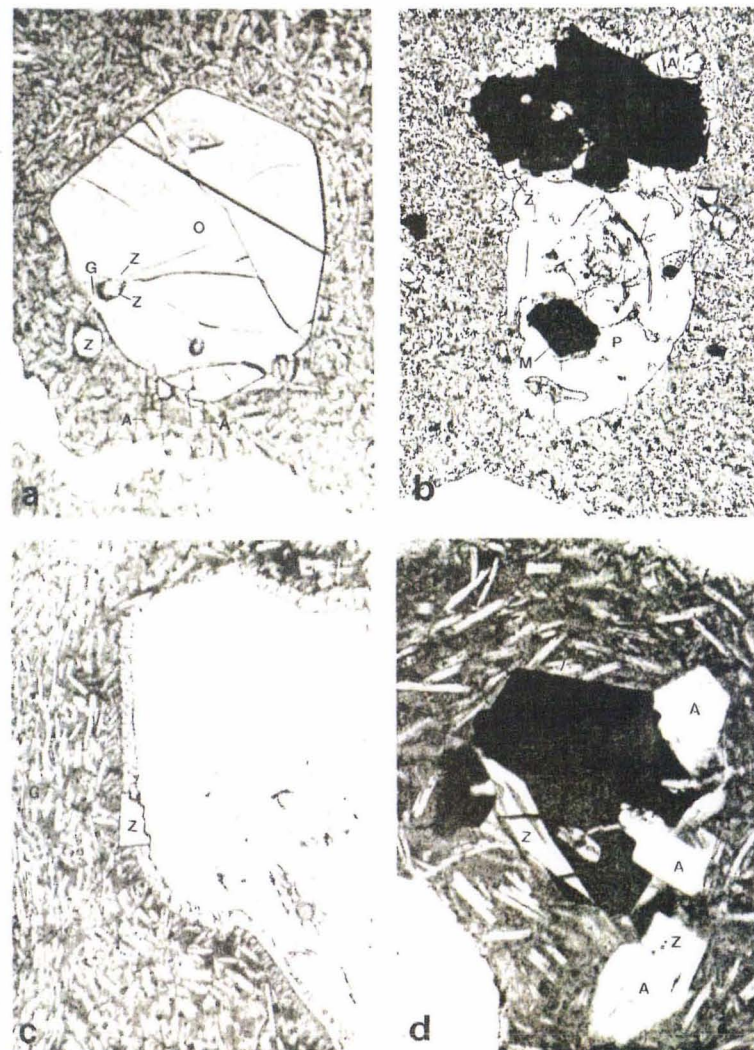


FIG. 7. Photomicrographs of glomerocrysts in Serrate, Devils Orchard, and Highway lava flows from the COM lava field. O, olivine; Z, zircon; A, apatite; P, pyroxene; M, magnetite; G, glass. (a) Fe-rich olivine (Fa_{88}) with glass and small zircon cubes included in embayments. Zircon is partly included by olivine; larger apatite crystals penetrate the olivine rim. Crystal cluster is approximately $550 \mu\text{m} \times 500 \mu\text{m}$ (DO2). (b) Fe-rich augite (Fs_{48}) and magnetite containing zircon and apatite inclusions. Crystal cluster is approximately $750 \mu\text{m} \times 300 \mu\text{m}$ (Se2). (c) Anorthoclase megacryst and small zircon crystal in the reaction rim. The rim is composed of brown glass and small feldspar laths having approximately the same composition as the groundmass feldspar. The feldspar megacryst is approximately $90 \mu\text{m} \times 850 \mu\text{m}$ (DO2). (d) Magnetite and associated zircon and apatite crystals. Crystal cluster is approximately $350 \mu\text{m} \times 400 \mu\text{m}$ (Hy3).

oriented plagioclase laths. Rare phenocrysts ($> 500 \mu\text{m} \times 500 \mu\text{m}$) and microphenocrysts of olivine, plagioclase, apatite, and opaque minerals also occur throughout the groundmass.

Much of the crystalline groundmass is formed by very small crystals, 1–25 μm in largest dimension. The smallest groundmass crystal sizes are $< 1 \mu\text{m}$ (e.g., TMF3) and the largest are $\sim 100 \mu\text{m}$ (as in BT1). Only one sample, Hy1, has a continuous range of crystal sizes from large groundmass to microphenocrysts to phenocrysts. The rest of the samples consist of either groundmass and microphenocrysts or groundmass and phenocrysts and/or megacrysts. Much of the glass in these rocks includes large numbers of microlites (e.g., TMF4 and Hy3). The glass ranges from black (BT1) to pale brown (DO2).

Four trachybasalts carry very fine-grained autoliths that contain glass darker than that of the groundmass of the host rocks. The compositions of minerals in the autoliths approximate those of the same minerals in the host groundmass in three of the trachybasalts (TMF1, TMF2, and BC2) but not in the fourth (BD2). In the last autolith, olivine is more Fe rich than phenocrysts in the host rock but is less Fe rich than groundmass olivine. Pyroxene is more Fe rich than the groundmass pyroxene, and both pyroxene and feldspar are less calcium-rich than the same minerals in the host rock.

Glass globules, rodlike laths, and other minute crystal inclusions are common in groundmass olivine and plagioclase. In addition, clusters of very small crystals grown together form raft structures. These clusters are of olivine or plagioclase or are a combination of olivine and plagioclase. In several samples, the small clusters are formed by opaques, apatite, and glass (NC1, BC3, and Se1). Pronounced trachytic texture and flow structures caused by the alignment of plagioclase laths and flow-elongated, aligned vesicles are conspicuous in several rocks (e.g., TMF2, Se1, and Se3) and faint in several others (e.g., BD2, BC2, and Se2).

Fe Ti oxides are ubiquitous throughout these rocks as glomerocrysts, megacrysts, phenocrysts, and microphenocrysts, but are mainly in the groundmass. Locally small inclusions of magnetite occur in crystals of olivine, pyroxene, and/or plagioclase and are common as large, individual crystals in glomerocryst assemblages (Fig. 7b and d). In several rocks (DO2, Hy2, and Hy3) the oxides are predominantly subhedral as inclusions but euhedral otherwise. In the Serrate flows (Se2 and Se3), both subhedral and euhedral crystals occur as inclusions and as individual crystals.

MINERALOGY

Olivine

The iron-rich nature of COM-A rocks is reflected in their olivine compositions (Table 6). Olivine occurs in all the flows and ranges in size from microlites (1–2 μm) to phenocrysts $> 1 \text{ mm}$. The compositions of olivine extend from Fa_{40} to Fa_{93} for all 22 rocks (Fig. 8).

Olivine in the basalt (BT1) has an average groundmass composition of $\sim \text{Fa}_{52}$ and microphenocryst core compositions of $\sim \text{Fa}_{47}$. The groundmass also contains several olivine crystals that are different from the average, reaching compositions as iron rich as Fa_{66} and as magnesian as the microphenocryst cores (Fig. 8). These olivines are much more iron rich than typical olivines in SRP basalts, which range as low as Fa_{20} in phenocrysts and rarely exceed Fa_{50} in the groundmass (Stout & Nicholls, 1977). In COM-A rocks, most microphenocryst rim compositions overlap the coexisting groundmass compositions, but in SRP basalts many phenocryst and microphenocryst rim compositions do not. In marked contrast to olivines in COM-A basalt, the most magnesian olivine phenocrysts in the SRP basalts, including those from Kings Bowl, carry inclusions of Mg Al-rich, brown spinel. No brown spinel-bearing olivine has been found in any COM-A rocks.

TABLE 6
Electron microprobe analyses of olivine

	BT1 Basalt					
	Mph c	Mph m	Mph r	Gm av	Gm hi	Gm lo
SiO ₂	35.57	35.38	35.12	34.62	33.52	35.11
FeO	39.49	39.59	40.54	42.57	50.55	39.68
MnO	0.63	0.67	0.69	0.74	0.98	0.68
MgO	24.33	23.76	22.91	21.28	13.84	24.42
CaO	0.31	0.36	0.48	0.42	0.64	0.32
Total	100.33	99.76	99.74	99.63	99.53	100.21

	BT2 Trachybasalt					
	Mph c	Mph m	Mph r	Gm av	Gm hi	Gm lo
SiO ₂	34.56	33.73	33.93	33.89	33.01	33.65
FeO	42.04	42.73	44.03	42.92	45.82	41.05
MnO	0.84	0.88	0.90	0.91	1.04	0.88
MgO	22.28	21.25	20.02	20.82	18.69	22.10
CaO	0.31	0.27	0.34	0.44	0.31	0.89
Total	100.03	98.86	99.22	98.98	98.87	98.95

	Se1 Tristanite				
	Ph c	Ph m	Ph r	Gm av	Gm l
SiO ₂	33.44	33.44	33.31	33.34	33.31
FeO	49.83	49.91	49.99	50.41	52.59
MnO	1.05	1.08	1.09	1.12	1.29
MgO	15.79	15.88	15.66	15.05	12.87
CaO	0.47	0.44	0.47	0.47	0.53
Total	100.58	100.75	100.52	100.39	100.59

	Se2 Trachyte								
	Glm c	Glm m	Glm r	Mph c	Mph m	Mph r	Gm av	Gm hi	Gm lo
SiO ₂	30.68	31.07	30.98	31.60	31.27	31.56	31.25	31.44	31.54
FeO	63.54	63.61	62.14	60.33	59.98	60.08	60.72	61.59	60.17
MnO	1.73	1.68	1.68	1.60	1.67	1.69	1.78	1.67	1.76
MgO	4.45	4.55	5.20	7.07	7.04	7.04	6.14	5.23	6.52
CaO	0.66	0.61	0.70	0.54	0.66	0.59	0.68	0.64	0.66
Total	101.06	101.52	100.70	101.14	100.62	100.96	100.57	100.57	100.65

Mph, microphenocryst; c, core; m, middle; r, rim; Gm, groundmass; av, average; hi, highest FeO; lo, lowest FeO; Gm l, groundmass outside of average; Ph, phenocryst; Glm, glomerocryst.

Four Trench Mortar Flat trachybasalts carry the most magnesian olivine in the 22 COM-A rocks studied (Fig. 8). Only one trachybasalt (BD2) has phenocryst-sized olivine, but these phenocrysts are not as magnesian as microphenocryst-sized olivine in the Trench Mortar Flat flows. The phenocrysts are $\sim \text{Fa}_{50}$, but three of the Trench Mortar Flat flows have olivine markedly less Fe rich (Fa_{40}). The groundmass olivine compositional range in all the trachybasalts is Fa_{40-70} . Typically, the groundmass composition overlaps those of the rims and often the cores of the larger phases, but some moderate-sized microphenocrysts in COM-A trachybasalts have compositions different from the groundmass (e.g., BC2; Fig. 8).

Olivine compositions in tristanites span the range between the trachybasalts and trachytes. One Serrate tristanite (Se1) has olivine compositions that vary from Fa_{63} (phenocryst) to Fa_{68} (groundmass). The groundmass olivine composition is similar to that of the most Fe-rich groundmass olivine in trachybasalts ($\sim \text{Fa}_{66-70}$) and also to that of the megacryst and microphenocrysts (Fa_{67-70}) in another tristanite (Hy1). The groundmass

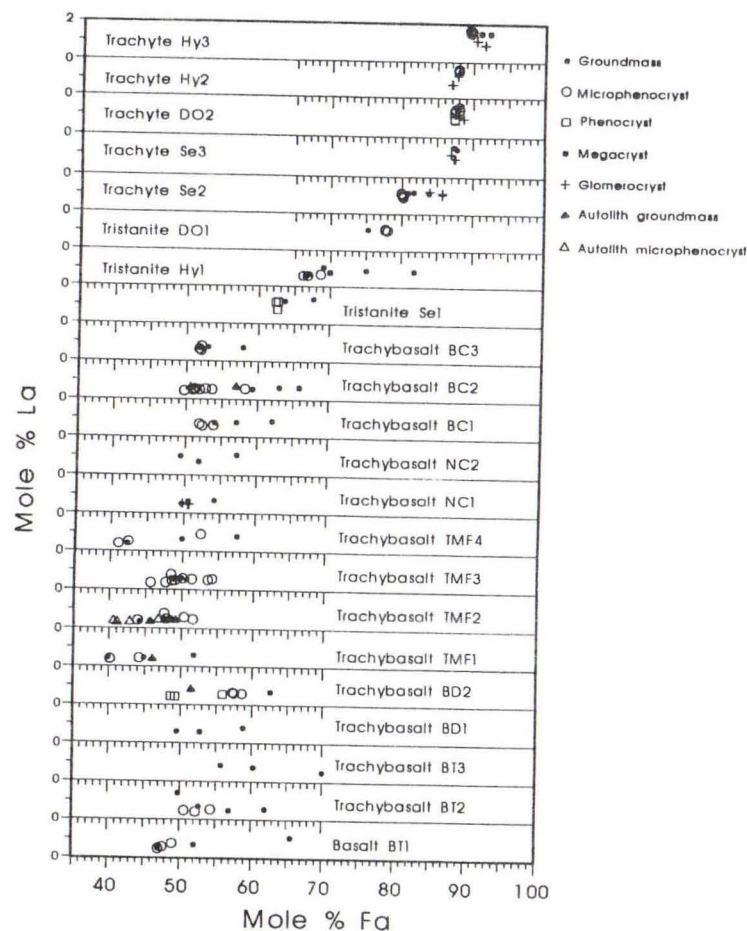


FIG. 8. Compositions of olivines in COM-A rocks. Mole % Fa = 100 - (Fo + La + Tp). La and Tp are larnite and tephroite, respectively. The vertical scale for each rock runs from 0 to 2 mol % La.

composition in Hy1, however, extends to Fa_{82} and overlaps the most magnesian olivine in the trachytes (Se2). The range of only ~5 mol% in olivine compositions in Se1 and in the tristanite DO1 (Fa_{75-78}) is more limited than that in the basalt and trachybasalts, but is comparable with that in most of the trachytes.

Compositions of all four sizes of olivine crystals—groundmass, microphenocrysts, phenocrysts, and glomerocrysts—in 4 of the 5 trachytes fall within a small range, ~ Fa_{87-93} (Fig. 8, Table 6). In three trachytes (Se3, DO2, and Hy2), the compositions of all sizes in each

of the three rocks are almost identical. An example is a trachyte (DO2) in which all four sizes are in the limited range of Fa_{87-93} mol%.

As expected in fayalitic olivine, high FeO contents are concomitant with high MnO contents. The MnO content of olivine from the COM-A basalt and trachybasalts ranges from 0.45 wt.% (NC1) to 1.27 wt.% (BT3) and from ~1 wt.% (Se1 and Hy1) to ~1.8 wt.% (Se2, Hy2, and Hy3) in the more fayalitic olivines in tristanites and trachytes. The MnO content of groundmass olivine generally overlaps the rim contents of larger phases except in tristanites and trachytes. In these rocks, the MnO content of the glomerocryst and megacryst olivine generally overlaps that of the microphenocrysts, but is ~0.5 wt.% less than that in groundmass olivine.

Cr_2O_3 is below detection (0.07 wt.%) in olivines from all COM-A rocks but one. Cr_2O_3 reaches detection limit in a megacryst in a tristanite flow (Hy1). This olivine is the most magnesian (Fa_{67}) megacryst in the tristanites and trachytes.

Pyroxene

Pyroxene compositions, like olivine compositions, reflect the Fe-rich nature of COM-A rocks. Like pyroxenes in SRP basalts, pyroxenes in the COM-A rocks are dominantly high-calcium augite. However, low-calcium pyroxenes occur in some COM-A rocks (Table 7).

TABLE 7

Electron microprobe analyses of pyroxene, including coexisting pyroxene in TMF3 (BT1 has no analyzed pyroxene)

	TMF3 Gm	TMF3 Gm	BT2 Gm	Se1 Gm	Se2 Glm c	Se2 Glm m	Se2 Glm r
SiO ₂	42.66	40.27	43.85	42.41	48.82	49.05	48.83
TiO ₂	5.00	0.60	6.25	0.47	0.71	0.67	0.68
Al ₂ O ₃	4.24	3.84	4.20	4.81	1.87	1.94	1.77
FeO	29.08	35.53	22.25	43.78	23.25	23.47	22.90
MnO	0.55	0.65	0.48	0.95	0.62	0.59	0.52
MgO	9.77	16.22	4.99	5.45	6.57	6.57	6.59
CaO	8.88	2.24	15.95	0.96	17.01	16.53	16.92
Na ₂ O	0.37	1.04	0.53	0.60	0.36	0.38	0.39
Total	100.55	100.39	98.50	99.43	99.21	99.20	98.69

Classification determined with computer program PX (Cebria Gomez, 1990). Gm, groundmass; Glm, glomerocryst; c, core; m, middle; r, rim.

Although few of the COM-A rocks have microscopically identifiable pyroxene in the groundmass, pyroxene was identified by automated electron-microprobe modal analyses in the groundmass of all 22 samples. The extremely small crystal size of most pyroxene in these rocks commonly prohibits accurate analysis by electron microprobe. Acceptable analyses of pyroxene were obtained in 18 of the 22 rock samples (Fig. 9). Additional identified submicroscopic crystals were all high-calcium pyroxene (estimated to contain > ~15 wt.% CaO from 1-s counts).

Groundmass pyroxene in the COM-A basalt (BT1) has ~17 wt.% CaO and ~19 wt.% FeO, estimated from 1-s counts. These estimated amounts of CaO and FeO are similar to typical augite compositions in period A Kings Bowl basalts and in SRP basalts generally: ~19 wt.% CaO and ~16 wt.% FeO (Leeman, 1974; Stout & Nicholls, 1977).

Trachybasalts have augite only in the groundmass; the average composition is ~16 wt.%

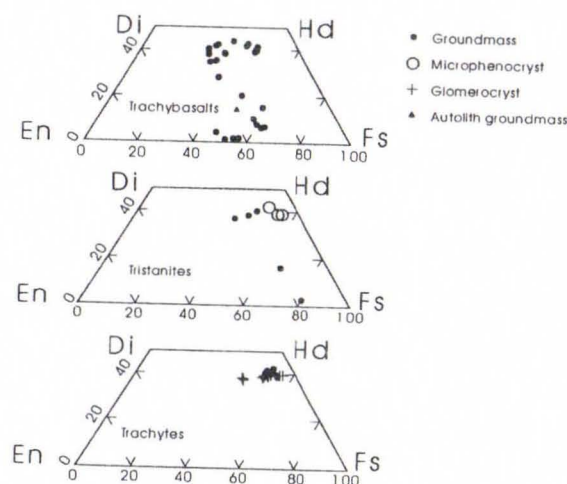


FIG. 9. Compositions of pyroxenes in COM-A rocks, in mole% En, Fs, Wo.

FeO. Three of 13 trachybasalts have low-calcium pyroxene in the groundmass. In a Trench Mortar Flat flow (TMF3), enstatite coexists with augite; in Big Crater flows, pigeonite has CaO from ~3 to 5 wt.% and FeO from ~32 to 35 wt.% (BC2), and ferrosilite has CaO ~1 wt.% and FeO ~34 wt.% (BC3). Coexisting high- and low-calcium pyroxene in the groundmass (TMF3; Table 7) is unusual in basaltic rocks of the SRP volcanic province (Stout & Nicholls, 1977).

One trachybasalt (BD2) has low-calcium (~6 wt.%) pyroxene in a fine-grained autolith (Fig. 9). The FeO content of this pigeonite is ~29 wt.%. The host rock has augite of two compositions: one is like the average SRP augite (FeO ~16 wt.% and CaO ~19 wt.%), and the other pyroxene contains an amount of FeO similar to the autolith pigeonite (~27 wt.%) but has higher CaO (~13 wt.%). The olivine and feldspar in the autolith are also different in composition from those in the host rock.

High- and low-calcium pyroxenes, including augite, pigeonite, and ferrosilite, occur in the tristanites. All these pyroxenes have high FeO contents which range from Fs_{38-41} in groundmass augite and Fs_{47-54} in microphenocryst augite from the Devils Orchard tristanite (DO1) through Fs_{65} in groundmass pigeonite in the Highway tristanite (Hy1) to Fs_{80} in groundmass ferrosilite in the Serrate tristanite (Se1), the highest FeO of any pyroxene in the 22 COM-A rocks (Fig. 9).

Although the COM-A low-silica rocks generally have groundmass pyroxene similar in iron composition to that in most SRP basalts, both tristanites and trachytes carry pyroxenes as glomerocrysts and in the groundmass that are more Fe rich. In trachytes, groundmass augite ranges between 21 and 30 wt.% FeO; ~28 wt.% (~ Fs_{50}) is the most common value. Glomerocryst augite in these rocks ranges from 23 to 31 wt.% FeO; again, 28 wt.% is the most common value. The Ca-rich pyroxenes are all classified as augite according to the IMA classification (Morimoto, 1989).

TiO_2 in pyroxene spans a broad range, from 0.4 to nearly 5 wt.% in COM-A rocks just as it does in SRP basalts. Al_2O_3 also spans a broad range (from 0.6 to 4 wt.%). Both TiO_2 and

Al_2O_3 show no discernible pattern with respect to zoning or abundance in pyroxene type. Cr_2O_3 and ZnO are below detection (0.07 and 0.24 wt.%) in all analyzed pyroxenes but one; 0.17 wt.% Cr_2O_3 occurs in the glomerocryst pyroxenes in trachyte DO2.

Pyroxene occurs as porphyroblasts and in the matrix of the two metamorphic xenoliths (78K34 and 78K158). Augite and enstatite porphyroblasts coexist with ferrosilite in the matrix of one xenolith (78K34). The other xenolith has only enstatite in both size ranges (Fig. 10).

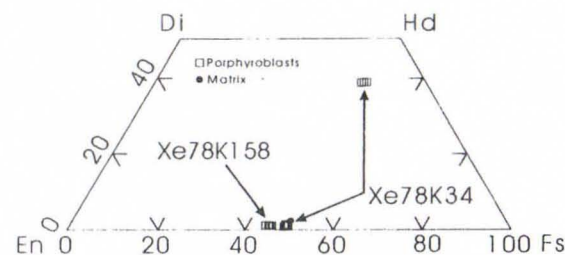


FIG. 10. Compositions of pyroxenes in xenoliths from COM-A rocks.

Feldspar

Plagioclase is the dominant groundmass phase in all the flows and ranges in size from microlites (~1–2 μm) to megacrysts >1 mm across. Feldspars in the COM-A rocks cover a compositional range that includes plagioclase (oligoclase to labradorite), anorthoclase, and sanidine (Fig. 11). Feldspars in COM-A rocks are consistently more alkali rich than are feldspars in SRP basalts, where most compositions fall in the labradorite field. Plagioclase in Kings Bowl flows, for example, ranges from a groundmass composition of An_{53} to phenocrysts as calcic as An_{71} . Groundmass feldspar in one Kings Bowl rock, however, averages An_{35} with >6 mol% Or (Stout & Nicholls, 1977). Electron-microprobe analyses of feldspar in four representative rocks are given in Table 8 and the compositions of all analyzed feldspars are illustrated in Fig. 11.

Groundmass and microphenocryst plagioclase in the COM-A basalt (BT1) has a limited compositional range, An_{41-45} , and Or contents of ~4 mol%. A patchy zoned microphenocryst is slightly more calcic, having a core composition of ~ An_{47} and a rim composition of ~ An_{44} .

Plagioclase in the trachybasalts also has a limited range in composition. Groundmass plagioclase compositions generally overlap rim compositions of larger crystals when they are present (Fig. 11). Only 1 of 13 trachybasalts carries plagioclase phenocrysts. That sample (BD1) has two distinct phenocryst compositions, one which is overlapped by groundmass compositions (An_{33-39}) and another that is more calcic core to rim (An_{47-45}). This trachybasalt is also one of only three trachybasalts that have anorthoclase (~ $An_{25}Ab_{62}Or_{13}Cel_{c1}$ to ~ $An_{21}Ab_{64}Or_{14}Cel_{c2}$) in the groundmass. All three anorthoclase-bearing rocks have coexisting plagioclase (~ An_{42}) in the groundmass. Two Trench Mortar Flat trachybasalts have megacrysts (1–2 mm in length) of andesine composition (~ An_{47}). The megacrysts are corroded and have very narrow or no reaction rims. One of these trachybasalts (TMF1) also has a second megacryst having a uniform core to rim

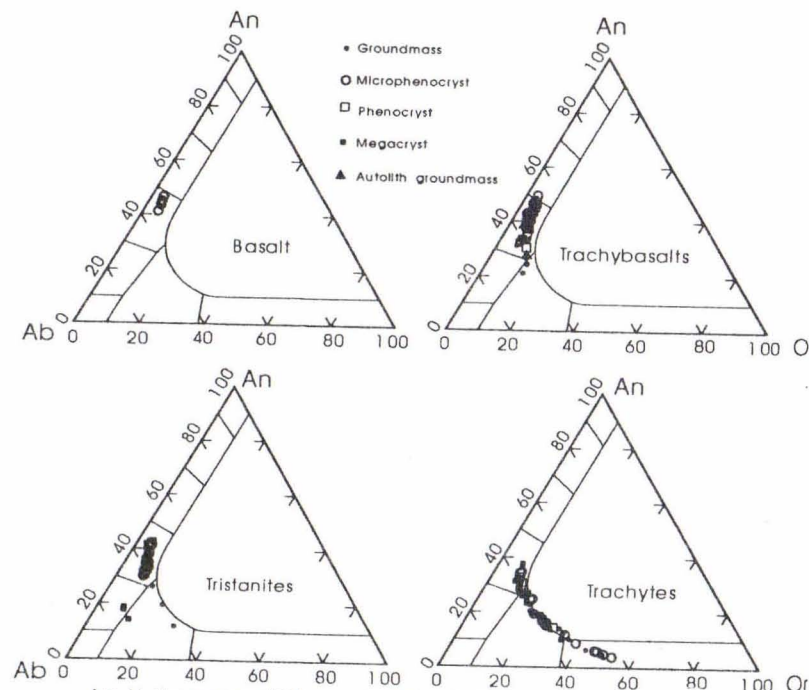


FIG. 11. Compositions of feldspars in COM-A rocks. Mole% Ab = 100 (An + Or + Cel).

composition of $\sim \text{An}_{33}$. The groundmass plagioclase in these rocks ranges from An_{36} to An_{45} . Two other trachybasalts have feldspar in autoliths. Plagioclase in an autolith in BC2 has a composition range ($\sim \text{An}_{42}\text{Ab}_{54}\text{Or}_{4}\text{Cel}_{11}$ to $\sim \text{An}_{39}\text{Ab}_{56}\text{Or}_{5}\text{Cel}_{11}$) approximately the same as the plagioclase in the groundmass of the host rock ($\sim \text{An}_{43}\text{Ab}_{53}\text{Or}_{4}\text{Cel}_{11}$ to $\sim \text{An}_{38}\text{Ab}_{57}\text{Or}_{5}$). Plagioclase in an autolith in (BD2) has a distinctly different composition ($\sim \text{An}_{28}\text{Ab}_{61}\text{Or}_{10}\text{Cel}_{11}$) from that of the host groundmass plagioclase ($\sim \text{An}_{41}\text{Ab}_{54}\text{Or}_{5}\text{Cel}_{11}$).

Andesine ($\sim \text{An}_{32-36}$) in three tristanites (Se1, DO1, and Hy1) occurs as megacrysts, phenocrysts or microphenocrysts, and as groundmass crystals. The groundmass plagioclase compositions overlap the rims of only some of the larger phases. Both the Serrate tristanite (Se1) and the Devils Orchard tristanite (DO1) have minor amounts of anorthoclase in the groundmass, ranging from $\sim \text{An}_{26}\text{Ab}_{59}\text{Or}_{13}\text{Cel}_{2}$ (DO1) to $\sim \text{An}_{12}\text{Ab}_{50}\text{Or}_{27}\text{Cel}_{2}$ (Se1). The Highway tristanite (Hy1) has only andesine in the groundmass ($\sim \text{An}_{34}$) but carries megacrysts having compositions distinctly different from each other. One megacryst is andesine. Another megacryst has core and rim compositions of oligoclase ($\sim \text{An}_{18}\text{Ab}_{73}\text{Or}_{9}\text{Cel}_{11}$) and a middle composition of anorthoclase ($\sim \text{An}_{15}\text{Ab}_{73}\text{Or}_{12}\text{Cel}_{11}$) (Fig. 11).

Feldspars from the trachytes show a wide range in composition (Fig. 11) but anorthoclase is the dominant feldspar. The feldspar compositions range from calcic andesine phenocrysts

TABLE 8
Electron microprobe analyses of feldspar

	BT1 Basalt				BT2 Trachybasalt				Se1 Tristanite				Se2 Trachyte			
	Mphl c	Mphl m	Mphl r	Mph2 c	Mph2 m	Mph2 r	Gm ar	Mph c	Mph m	Mph r	Gm ar	Mph2 c	Mph2 m	Mph2 r	Gm ar	Gm2
SiO ₂	57.19	57.03	58.05	56.62	56.55	57.39	57.43	57.65	57.59	57.55	59.66	57.75	57.57	59.66	60.09	
Al ₂ O ₃	26.34	26.62	25.94	27.14	26.87	26.20	26.38	25.63	25.47	25.81	23.67	25.81	25.84	23.67	24.30	
CaO	9.14	9.33	8.62	9.66	9.65	8.97	9.00	8.43	8.53	8.69	6.75	8.65	8.48	6.75	6.64	
BaO	0.11	0.11	0.13	0.10	0.16	0.16	0.12	0.19	0.14	0.14	0.45	0.17	0.15	0.45	0.34	
Na ₂ O	5.98	5.83	6.24	5.68	5.69	5.92	6.04	6.12	6.12	6.12	6.08	6.18	6.12	6.08	6.83	
K ₂ O	0.74	0.71	0.82	0.65	0.64	0.78	0.77	0.80	0.78	0.74	1.16	0.74	0.81	1.16	1.29	
Total	99.50	99.63	99.80	99.85	99.56	99.42	99.74	98.82	98.63	98.67	98.52	98.67	98.97	98.52	99.49	
	BT1 Basalt				BT2 Trachybasalt				Se1 Tristanite				Se2 Trachyte			
	Mphl c	Mphl m	Mphl r	Mph2 c	Mph2 m	Mph2 r	Gm ar	Mph c	Mph m	Mph r	Gm ar	Mph2 c	Mph2 m	Mph2 r	Gm ar	Gm2
SiO ₂	58.73	58.15	59.17	57.61	60.32	59.07	61.43	58.06	57.93	58.20	59.33	58.20	57.93	58.20	63.38	64.96
Al ₂ O ₃	25.69	25.56	24.73	26.11	24.56	25.12	23.30	25.93	26.16	25.78	24.63	25.78	26.16	25.78	21.38	20.66
CaO	8.05	8.16	7.52	8.99	6.94	7.48	6.31	8.60	8.67	8.65	7.53	8.65	8.67	7.53	3.99	2.47
BaO	0.28	0.28	0.26	0.18	0.31	0.18	<0.17	0.23	0.24	<0.17	0.22	0.23	0.24	<0.17	0.81	1.11
Na ₂ O	6.33	6.36	6.61	6.02	6.68	6.74	7.12	6.16	6.12	6.18	6.61	6.16	6.12	6.18	6.67	6.68
K ₂ O	0.99	0.96	1.16	0.79	1.32	1.18	1.48	0.90	0.86	0.85	1.13	0.90	0.86	0.85	3.35	4.68
Total	100.07	99.47	99.45	99.70	100.13	99.77	99.64	99.80	99.98	99.66	99.45	99.66	99.98	99.66	99.58	100.36
	BT1 Basalt				BT2 Trachybasalt				Se1 Tristanite				Se2 Trachyte			
	Mphl c	Mphl m	Mphl r	Mph2 c	Mph2 m	Mph2 r	Gm ar	Mph c	Mph m	Mph r	Gm ar	Mph2 c	Mph2 m	Mph2 r	Gm ar	Gm2
SiO ₂	59.64	59.54	59.13	58.69	58.81	59.52	59.13	58.06	57.93	58.20	59.33	58.20	57.93	58.20	63.38	64.96
Al ₂ O ₃	23.98	23.79	24.00	24.01	23.87	23.88	23.30	25.93	26.16	25.78	24.63	25.78	26.16	25.78	21.38	20.66
CaO	6.47	6.43	6.76	6.92	6.67	6.31	6.31	8.60	8.67	8.65	7.53	8.65	8.67	7.53	3.99	2.47
BaO	0.23	0.32	0.24	0.48	0.65	0.78	0.54	0.23	0.24	<0.17	0.22	0.23	0.24	<0.17	0.81	1.11
Na ₂ O	6.76	6.86	6.69	6.44	6.50	6.55	6.62	6.16	6.12	6.18	6.61	6.16	6.12	6.18	6.67	6.68
K ₂ O	1.44	1.41	1.38	1.43	1.50	1.82	1.68	0.90	0.86	0.85	1.13	0.90	0.86	0.85	3.35	4.68
Total	98.52	98.35	98.20	97.97	98.00	98.86	97.58	99.80	99.98	99.66	99.45	99.66	99.98	99.66	99.58	100.36

BT1: Mphl is an average of 4 microphenocrysts; Mph2 is an average of 2 partly corroded microphenocrysts; c: core; m: middle; r: rim; Gm ar: groundmass average composition; BT2: Mph r1, Gm1: composition different from average composition; Se1: Mega r: crystal has approximately same core and middle composition as the phenocryst but is corroded and has a different rim composition; Mph1, Mph2: two groups of microphenocrysts; Gm1, Gm2: crystals with compositions different from average; Se2: several crystals have the composition $\sim \text{An}_{31}\text{Ab}_{60}\text{Or}_{18}\text{Cel}_{11}$ but are too small for accurate analysis ($< 1 \mu\text{m}$). Gm: glomerocryst; Ph: phenocryst.

and microphenocrysts ($\sim \text{An}_{37}\text{Ab}_{54}\text{Or}_{7}\text{Cel}_1$) in DO2 to sanidine microphenocrysts ($\sim \text{An}_{42}\text{Ab}_{42}\text{Or}_{53}\text{Cel}_1$) in Hy3. Anorthoclase in trachytes also has a high celsian component (1–2 mol%) in most of the groundmass but up to 3–5 mol% in the groundmass of some samples, as in DO2 ($\text{Cel}_{2.6-5.1}$) and Se3 ($\text{Cel}_{3.5}$). Three of the five trachytes carry megacrysts of andesine. The megacrysts range from $\sim \text{An}_{30}$ to An_{38} , have corroded centers and reaction rims, and, in one of the trachytes (Se2), crystals of feldspar are adjacent to or intergrown with the megacryst rims. Megacrysts of anorthoclase also occur in three trachytes, one of which (Se3) also carries an andesine megacryst. The cores of anorthoclase megacrysts range from $\sim \text{An}_{24}\text{Ab}_{60}\text{Or}_{15}\text{Cel}_1$ (Se3) to $\sim \text{An}_{15}\text{Ab}_{55}\text{Or}_{28}\text{Cel}_2$ (DO2, Fig. 7c, zircon intergrown in the reaction rim). These megacrysts show odd zoning. Locally, the middle or rim composition is higher in An and lower in Or than the cores. None of these compositions match the compositions of other anorthoclase feldspars present in the rocks. Leeman *et al.* (1976) observed 'resorbed' anorthoclase in several COM-A rocks.

Xenoliths in some COM-A flows carry a variety of feldspars as phenocrysts, microphenocrysts, and in the groundmass (Fig. 12). One pumiceous xenolith (79K25)

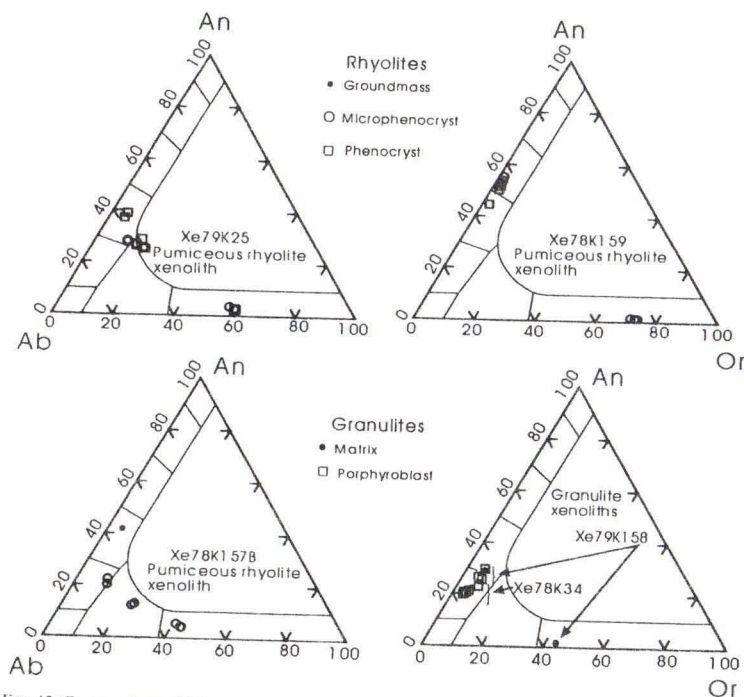


FIG. 12. Compositions of feldspars in xenoliths from COM-A rocks. Mole % Ab = $100 - (\text{An} + \text{Or} + \text{Cel})$.

contains sanidine, anorthoclase, and andesine phenocrysts. The andesine phenocryst has an anorthoclase rim and one anorthoclase microphenocryst has a sanidine rim (Cel_3), which is similar to the composition of the groundmass feldspar. Two other pumiceous rhyolite xenoliths contain labradorite, one (78K159-1) as phenocrysts and the other (78K159-2) as coexisting microphenocrysts of labradorite and sanidine, which have celsian rim compositions of 3–4 mol%. The fourth pumiceous rhyolite xenolith (78K157B) has anorthoclase and sanidine microphenocrysts (Cel_{-4}) in an andesine groundmass, $\sim \text{An}_{42}$.

The granulite xenoliths (78K34 and 78K158) have oligoclase as porphyroblasts and in the matrix. Coexisting sanidine occurs in the matrix of 78K158. The host lava flow of one xenolith (78K34) has anorthoclase as both phenocrysts and groundmass.

Fe-Ti oxides

All COM-A flows contain Fe-Ti oxides; magnetite is abundant, ilmenite is scarce. Like pyroxene, some small crystals of ilmenite were identified by microprobe modal analysis but could not be located or successfully analyzed. Representative electron microprobe analyses of ilmenite-hematite and magnetite-ulvöspinel solid solutions are given in Tables 9 and 10. All Fe-Ti oxide analyses obtained are illustrated in Fig. 13.

TABLE 9
Electron microprobe analyses of ilmenite and magnetite, including BD1
(no ilmenite found in Se1)

	Ilmenite				Magnetite
	BT1 Gm	BT2 Mega	BD1 Gm	Se2 Mega	BT1 Basalt Gm av
SiO_2	0.10	< 0.03	0.50	< 0.03	0.10
TiO_2	48.22	48.91	47.70	49.57	24.87
Al_2O_3	0.20	0.17	0.29	0.15	2.07
Fe_2O_3	8.18	8.70	8.04	4.82	19.06
FeO	40.40	38.03	40.98	41.94	50.94
MnO	0.70	0.59	0.70	0.76	0.63
MgO	1.11	2.98	0.65	1.02	1.81
CaO	0.31	0.03	0.50	0.04	0.15
Total	99.22	99.41	99.36	98.30	99.63
		Mole % end-member			
Ht	8.34	8.40	9.34	4.85	

Gm, groundmass; Mega, megacryst; all ilmenite crystals coexist with magnetite. FeO and Fe_2O_3 calculated from stoichiometry; Gm av, average groundmass.

Ilmenite was identified in the groundmass of the basalt and 9 of the 13 trachybasalts, but not in the groundmasses of the tristanites or trachytes. Ilmenite does not occur as glomerocrysts, phenocrysts, or microphenocrysts in any of the COM-A rocks. Megacrysts of coexisting ilmenite and magnetite occur in two rocks, a trachybasalt (BT2) and a trachyte (Se2). In contrast, both ilmenite and coexisting magnetite are common in the groundmass and as microphenocrysts in SRP rocks (Stout & Nicholls, 1977).

The hematite component in ilmenite in COM-A rocks ranges from 2 to 9 mol%; the most

TABLE 10
Electron microprobe analyses of magnetite

BT2 Trachybasalt																
Mega c	Mega r	Ph l c	Ph l r	Ph2 c	Ph2 r	Mph l c	Mph l r	Mph2 c	Mph2 r	Gml	Gml	Gm2	Gm3			
n.d.	n.d.	0.12	0.14	0.09	0.19	0.10	0.10	0.12	0.11	0.24	0.24	0.15	0.20			
22.75	21.70	20.68	21.30	23.01	22.97	21.83	21.80	20.74	21.00	23.32	23.32	21.82	24.40			
2.43	2.49	3.08	2.48	2.63	2.39	2.41	2.32	3.29	2.48	1.44	1.44	2.27	1.42			
22.47	24.56	25.81	25.11	22.42	21.60	24.12	23.85	25.58	26.19	21.12	21.12	23.65	19.11			
48.31	47.76	46.72	47.36	48.69	49.18	49.02	48.81	47.46	47.49	50.33	50.33	48.96	51.19			
0.50	0.57	0.52	0.59	0.55	0.55	0.60	0.55	0.58	0.53	0.65	0.65	0.59	0.72			
2.19	1.94	2.23	2.05	2.40	1.89	1.33	1.31	1.87	1.89	0.98	1.21	1.05				
0.01	0.03	0.03	0.06	0.01	0.05	0.04	0.12	0.01	0.11	0.23	0.10	0.13				
98.66	99.05	99.19	99.09	99.80	98.82	99.45	98.88	99.64	99.79	98.31	98.75	98.22				
Mole % end-members																
Mt	31.32	34.19	35.71	34.90	30.81	30.10	33.60	33.41	35.30	36.21	29.91	33.21	27.05			
Usp	62.10	59.70	57.76	58.72	62.03	63.80	61.55	61.89	58.77	58.02	65.74	62.19	68.16			

Se2 Trachyte																
Ph c	Ph r	Mph c	Mph r	Gm	Glm c	Glm r	Mega	Mph l	Mph2	Gml	Gml	Gm2				
0.10	0.11	0.10	0.13	0.24	0.06	0.07	n.d.	n.d.	0.12	0.12	0.19	0.17				
21.15	20.53	20.94	19.82	19.79	23.24	22.17	24.44	23.14	18.04	14.58	14.58	18.81				
2.19	2.12	2.38	1.72	1.69	21.77	22.80	19.21	1.23	1.65	1.79	1.79	1.64				
26.76	27.56	26.66	28.26	28.55	51.10	49.87	51.55	21.90	30.75	36.52	36.52	29.08				
48.37	48.00	48.69	47.73	47.67	0.74	0.74	0.70	50.76	46.60	43.75	43.75	47.85				
0.59	0.63	0.58	0.60	0.59	0.85	0.80	0.67	0.76	0.59	0.58	0.58	0.41				
1.61	1.35	1.25	0.80	0.98	0.85	0.80	0.67	0.91	0.63	0.35	0.35	0.35				
0.02	0.03	0.05	0.09	0.14	n.d.	n.d.	0.01	n.d.	n.d.	n.d.	n.d.	n.d.				
100.79	100.33	100.65	99.15	99.65	99.01	97.87	97.81	98.76	98.38	97.76	97.76	98.31				
Mole % end-members																
Mt	36.80	38.17	39.85	39.99	30.95	32.80	27.45	31.21	44.11	52.95	52.95	41.73				
Usp	57.94	57.01	58.74	56.56	67.06	65.33	68.71	66.66	44.58	46.38	46.38	57.52				

Gm av. average groundmass; Mega, megacryst; Ph, phenocryst; Mph, microphenocryst; Glm, glomerocryst; c, core; r, rim; BT1 Gm and BT2 Megaocryst coexist with ilmenite (Table 9), n.d., not determined; FeO and Fe₂O₃ calculated from stoichiometry. Some crystals in Se2 show evidence of oxidation exsolution. Megacrysts coexist with megacrystic ilmenite (Table 9).

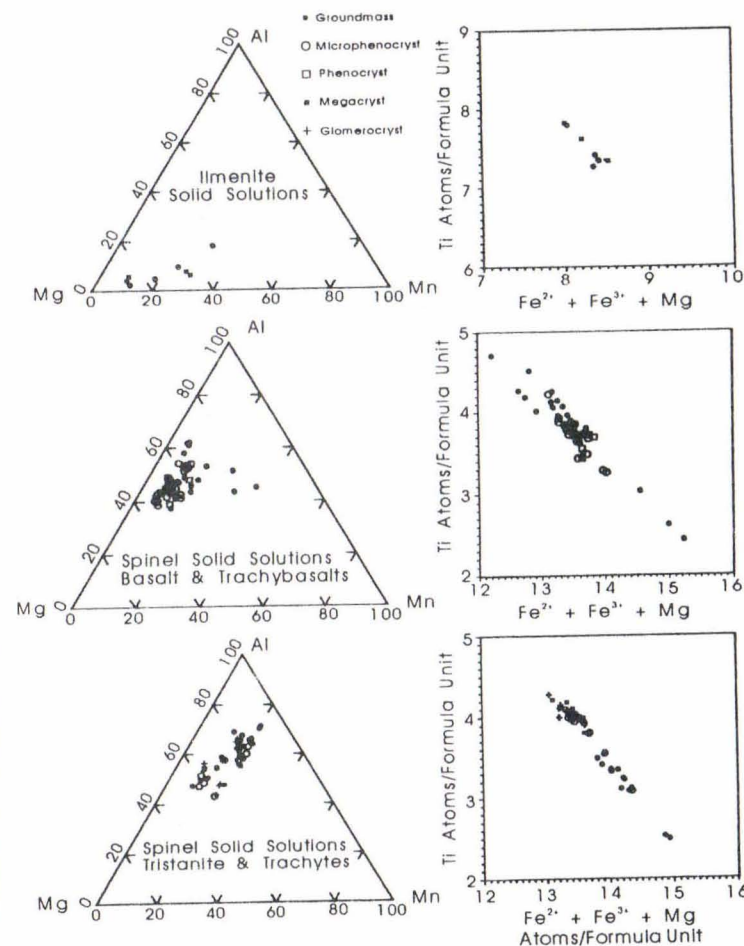


Fig. 13. Compositions of Fe-Ti oxides (ilmenite and magnetite) in COM-A rocks. Illustrated by the number of cations of major and minor oxides per formula unit.

common value is 7 mol%. Megacryst and groundmass ilmenite have approximately the same range in composition, 2.8 and 3.9 mol% hematite, respectively. The ilmenite in Kings Bowl basalts has a smaller range (5.7 mol% hematite; Stout & Nicholls, 1977) within the range shown by SRP rocks, ~5.11 mol%; the value of ~7 mol% hematite is most common, as it is in the COM-A rocks.

MnO in the analyzed ilmenites in the COM-A rocks has a very limited range, varying only

from ~0.6 to ~0.8 wt.%, MgO, however, shows some variation (from <1 to 3 wt.%) but there is no correlation with rock type or crystal size. These minor oxides cover ranges similar to those in SRP basalts. Ternary diagrams illustrating the cations of minor oxides are shown in Fig. 13.

Magnetite in the groundmass of the basalt is ~Usp₆₇. This is within the range of many SRP basalts (Usp₆₁₋₇₄), including the Kings Bowl basalts (Stout & Nicholls, 1977).

Magnetites in COM-A trachybasalts encompass the TiO₂ range found in magnetites in most SRP basalts, but also include amounts both larger and smaller (~Usp₆₀ to ~Usp₈₀) with the exception of one trachybasalt (BT3). In this rock, the microphenocrysts are in the same TiO₂ range as in the other trachybasalts, but magnetite in the groundmass is significantly lower, ranging from Usp₄₀ to Usp₅₀.

Magnetite in two tristanites (Sc1 and Hy1) occurs as rare, subhedral to euhedral microphenocrysts and as moderately abundant small crystals in the groundmass. The composition in both crystal sizes ranges from Usp₅₆ to Usp₅₉ in Sc1 and from Usp₆₈ to Usp₆₉ in Hy1. This small range includes a magnetite megacryst which coexists with an apatite megacryst, in addition to the microphenocryst and groundmass phases in Hy1. In contrast, magnetite in the tristanite DO1, which occurs only in the groundmass, has the lowest TiO₂ content of the three tristanites, ~Usp₅₄.

Most trachytes have groundmass magnetite compositions at or below Usp₆₀, dropping as low as Usp₄₄ in one Highway flow (Hy3). Magnetite found in glomerocrysts, and as inclusions in megacrysts in the trachytes are Usp₆₈₋₇₃. One trachyte (DO2), has two distinct magnetite compositions in the same glomerocryst: a magnetite inclusion in an olivine crystal in the glomerocryst has a core composition of Usp₇₂, which is approximately the same as the composition of a magnetite phenocryst in the host rock, whereas magnetite in a pyroxene crystal in the same glomerocryst is Usp₆₃.

The basalt (BT1), four trachybasalts (BD1, TMF1, TMF2, and TMF4), and one trachyte (DO2) have only groundmass Fe-Ti oxides, ~1-25 µm. The other 16 COM-A rocks have magnetite glomerocrysts and/or megacrysts, phenocrysts, and/or microphenocrysts in addition to small crystals in the groundmass. These significant size differences among the Fe-Ti oxides are accompanied by differences in magnetite composition in all rocks but the trachytes. Higher amounts of both Al₂O₃ (up to 3.6 wt.%) and MgO (up to 2.8 wt.%) generally occur in larger crystals (Fig. 13). However, when only groundmass magnetite is present in the rock, both Al₂O₃ and MgO are distinctly higher than they are in groundmass magnetite which coexists with larger crystals.

Although magnetite glomerocrysts and megacrysts have a similar range of TiO₂ contents (22-28 wt.%) throughout the COM-A rocks, they generally have low MgO contents in the trachytes, averaging only ~0.5 wt.%. This is approximately equal to the MgO contents of other magnetite in the trachytes, but megacrysts in the tristanite and groundmass magnetite in the basalt and trachybasalts have three times that amount. Rare megacrystic and glomerocrystic magnetites in the basalt and trachybasalts consistently have >2% MgO. Al₂O₃ contents of magnetite glomerocrysts and megacrysts generally show a similar, but less extreme, difference with rock type compared with MgO.

An obvious difference between SRP basalts and COM-A rocks is that a coexisting Cr-rich (~5 wt.% Cr₂O₃) groundmass magnetite typically occurs in the SRP basalts but not in the COM-A rocks. In COM-A rocks, Cr₂O₃ is generally below detection limit (0.08 wt.%). Additional differences between spinels in the COM-A rocks and spinels in the SRP basalts are occurrences of Mg-Al brown spinel and Cr-rich spinel (>10 wt.% Cr₂O₃) as inclusions in some olivine crystals in period A Kings Bowl and other SRP basalts, but not in COM-A rocks (Leeman, 1974; Stout & Nicholls, 1977).

Glass

Glass is present in all COM-A rocks and ranges from ~4% by volume (Hy1) to ~65% by volume (DO2) (Table 4). The range of silica content in the glass is 56-62 wt.% in the basalt (BT1) and 56-71 wt.% in trachybasalts. The range in silica content in the trachybasalts encompasses the SiO₂ ranges in glasses from both tristanites and trachytes, ~63-68 wt.%. All analyzed oxides show some variation within a rock, perhaps reflecting isolated patches of glass having different compositions. However, analysis of glass in these rocks is problematic because much of the glass is very dark and includes many microlites; it is a distinct possibility that some of the measured variation in glass composition is due to contamination by included microlites.

Accessory phases

Apatite is ubiquitous in the groundmass of SRP basalts and in the groundmass of COM-A rocks. In COM-A rocks, however, apatite also occurs as microphenocrysts or phenocrysts in the basalt and in most trachybasalts. Apatite is also found as megacrysts associated with magnetite (NC1 and Hy1) and in glomerocrysts associated with olivine ± pyroxene and magnetite in trachytes.

Zircon (10-50 µm) occurs in tristanites and trachytes where it is associated with either feldspar megacrysts or with glomerocrysts of olivine ± pyroxene, magnetite, and apatite.

SUMMARY OF CLASSIFICATIONS

The data presented in this paper suggest that the Craters of the Moon period A rocks represent magmas related to SRP basalts and to each other. The data from rock chemistry (Figs. 3 and 4), modal abundances (Fig. 6 and Table 4), and mineral compositions (Figs. 8-13) suggest that there are four rock types represented in the COM-A lava flows:

- (1) Basalts have an estimated color index > 30, SiO₂ contents > 48 wt.%, P₂O₅ contents > 2 wt.%, TiO₂ contents > 3 wt.%, modal feldspar plus glass < 80%, Fa contents of olivine microphenocrysts < 50%, and feldspar compositions in the andesine-labradorite range.
- (2) Trachybasalts have estimated color indices > 20 and may overlap the range for basalts, SiO₂ contents in the range 49-52 wt.%, P₂O₅ contents between 1.5 and 2 wt.%, TiO₂ contents between 2 and 3 wt.%, modal feldspar plus glass < 85%, Fa contents of olivine microphenocrysts < 60%, and feldspar compositions typically in the andesine-anorthoclase range, but with minor extensions into the lower labradorite range (Fig. 11).
- (3) Tristanites have estimated color indices between 10 and 20, SiO₂ contents in the range 54-57 wt.%, P₂O₅ contents between 1 and 0.5 wt.%, TiO₂ contents between 1 and 2 wt.%, modal feldspar plus glass between 80 and 90%, Fa contents of olivine microphenocrysts between 60 and 80%, and feldspar compositions in the andesine, oligoclase, and anorthoclase ranges.
- (4) Trachytes have estimated color indices < 10, SiO₂ contents > 60 wt.%, P₂O₅ contents < 0.3 wt.%, TiO₂ contents < 1.0 wt.%, modal feldspar plus glass > 90%, Fa contents of olivine microphenocrysts > 80%, and feldspar compositions in the lower andesine, anorthoclase, and/or sanidine ranges.

DISCUSSION

Relationships between the COM-A and SRP magmas

Petrographical, mineralogical, and chemical data constrain interpretations concerning the origin of the COM-A magmas and their relationship to magmas like those that supplied

the SRP basalt flows. Features suggesting a genetic link between the two kinds of magmas are as follows:

(1) distinctive chemical features common to both the COM-A flows and the SRP basalts—relatively low SiO_2 and high total alkali and iron contents;

(2) a phenocryst assemblage dominated by plagioclase and olivine and a paucity of clinopyroxene;

(3) Thompson space configurations (Fig. 5) suggesting a progressive chemical change from SRP basalts to COM-A trachytes.

Some mineralogical differences between the COM-A rocks and the rocks of the SRP can be attributed to different differentiation stages or to different P - T paths of crystallization. For example, the SRP basalts contain magnesian olivine with Mg-Al spinel inclusions and, commonly, coexisting ilmenite and Cr-rich magnetite whereas the COM-A rocks contain Fe-rich olivine, lack the Cr-rich and Mg-Al spinels, and contain little ilmenite.

Location of the vents for the COM-A and SRP rocks seems to correlate more strongly with the mineralogical and textural diversity than does age. Both the COM-A and Kings Bowl lava flows erupted ~2000–2500 yr B.P. but the Kings Bowl lava field is located near the centre of the SRP not along its edge as is the COM lava field. The differences between the magmas that formed the rocks at the two locations may be due to different compositions of the source rocks, different differentiation processes, or the COM-A magmas reaching later stages of the differentiation processes.

The existence of large crystals of pyroxene in glomerocrysts along with large crystals of olivine, apatite, and magnetite in the COM-A trachytes is very different from the occurrence of pyroxene in SRP basalts. Although 'starburst' glomerocrysts consisting of smaller crystals of olivine and pyroxene with plagioclase are fairly common in SRP basaltic rocks, large early crystals of pyroxene are rare to nonexistent. The role clinopyroxene might play in any differentiation process, however, could be complex. Clinopyroxene would be the liquidus phase in a dry melt with the composition of BT1 at pressures above ~0.6 GPa (Fig. 14), whereas pressures >0.8 GPa are required for clinopyroxene to be the liquidus phase in SRP basalts. It is possible that the large clinopyroxene phenocrysts in the COM-A rocks are the products of crystallization at intermediate crustal levels and that the habits and settings of clinopyroxene in rocks derived from the two kinds of magmas are the product of different differentiation stages rather than separate source rocks.

Other mineralogical differences are not easily reconciled with internal differentiation processes, and may indicate the possible influence of external processes such as crustal contamination. These include zircon inclusions in feldspar megacrysts and as part of the glomerocryst assemblages in the COM-A rocks; the presence of alkali feldspar megacrysts; and contrasting compositions of magnetite inclusions in olivine and pyroxene from one glomerocryst. Small square prisms and dipyramids of zircon accompany both feldspar megacrysts and glomerocrysts of olivine, pyroxene, magnetite, and apatite in the COM-A rocks. Coexisting alkali feldspar and zircon are found in pumice xenoliths in COM-A rocks, and the source rocks for the xenoliths may be the source of similar mineral pairs in the lava flows. Zircon occurs in embayments within large crystals of olivine in the glomerocrysts, is partly included by olivine (Fig. 7a), and shows no evidence of being resorbed. Olivine, however, does not occur in any of the xenoliths. Similarly, olivine does not occur in any of 31 COM xenoliths studied by Matty (1984). Interpretations consistent with the textural occurrences of zircon are: contamination by the feldspar + zircon-bearing xenoliths found in these rocks, or primary crystallization from the melts, or both.

Crustal xenoliths may not be a source for the large crystals of pyroxene in COM-A rocks because some xenoliths contain only orthopyroxene whereas others contain both

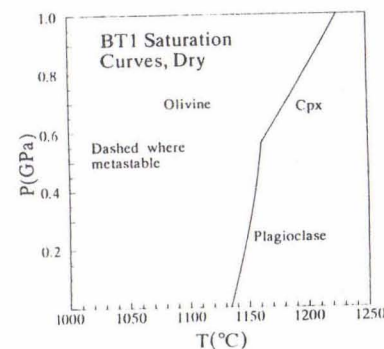


Fig. 14. Saturation curves for COM-A basalt, BT1, calculated from data of Ghiorso *et al.* (1983). Clinopyroxene is the liquidus phase at pressures greater than ~0.6 GPa whereas plagioclase is the liquidus phase at lower pressures. Olivine can be the liquidus phase only if the plagioclase or clinopyroxene saturation temperatures are depressed by other constituents such as H_2O and F.

orthopyroxene and clinopyroxene but only clinopyroxene is found in the glomerocrysts in the COM-A trachytes. Matty (1984) reported minor amounts of clinopyroxene (0.2 and 2.1%) without coexisting orthopyroxene in 2 of 31 COM xenoliths, but these xenoliths do not contain olivine, zircon, or apatite.

The possibility of deriving the COM-A basalt, BT1, from an SRP magma can be tested by mass balance calculations (Bryan *et al.*, 1969; Wright & Doherty, 1970; Stormer & Nicholls, 1978). An olivine basalt, collected from a depth of ~45 m in Crystal Ice Cave, Kings Bowl lava field (IV-7; Stout & Nicholls, 1977) may represent a possible precursor to a COM-A basaltic rock (BT1), because it has a P/K ratio (0.863) approximately the same as that in the COM-A basalt (0.871). Mass balance calculations (Table 11) give a sum of squares of residuals of 0.58 as a result of fractionating the phenocryst assemblage in the olivine basalt: olivine (~Fa₃₅), plagioclase (~An₅₆), and augite, and a typical magnetite phenocryst composition of ~Usp₆₈. Calculations with a slightly more magnesian-rich (earlier?)

TABLE 11

Results of mass balance calculations to test feasibility of deriving BT1 from an SRP basalt (IV7, Stout & Nicholls, 1977) by crystal sorting

Initial magma	Derivative magma	Oliv	Plag	Cpx	Mt	Sum squares of residuals
SRP basalt IV7	COM-A basalt BT1 (1)	-12.2	-32.6	-20.5	-3.9	0.58
SRP basalt IV7	COM-A basalt BT1 (2)	-12.2	-29.4	-19.7	-3.2	0.30

(1) Pyroxene Fe:Mg=0.58; (2) Pyroxene Fe:Mg=0.52. Numbers are grams of sorted phase per 100 g of initial magma. Negative values indicate phase is fractionated in the model.

pyroxene lowers the sum of squares of residuals to 0.3. The high amounts of material fractionated in this model (60–65%) is consistent with rare earth concentrations (Kuntz *et al.*, 1992) which suggest that significant amounts of fractionation are required to derive the least evolved COM basalts from SRP basalts and to account for the 1–8 times increase in concentration of rare earth elements in COM-A rocks relative to SRP olivine basalts. If the mass balance model for deriving COM-A basaltic magmas from the Kings Bowl magma is correct, then the rare earth elements should be concentrated in COM-A basalt by a factor of ~3 over the concentrations in the SRP lava flows.

Relationships between COM-A magmas

Coherent trends and nonzero intercepts on Pearce element ratio diagrams (Pearce, 1968; Nicholls, 1988) are consistent with genetic links between the COM-A rock types. If the chemical variations in the COM-A suite are due to sorting (fractionation and accumulation) of olivine $[(\text{Fe}, \text{Mg})_2\text{SiO}_4]$, plagioclase, clinopyroxene $[\text{Ca}(\text{Fe}, \text{Mg})\text{SiO}_3]$, apatite, and ulvöspinel, then the data for the rock suite should fall on a line with a slope of one on a plot of $(\text{Si} + \text{Ti} + 2.5 \text{ P})/\text{K}$ vs. $[0.25 \text{ Al} + 0.5(\text{Fe} + \text{Mg}) + 1.5 \text{ Ca} + 2.75 \text{ Na}]/\text{K}$.

To test whether the data actually conform to this sorting hypothesis, one can calculate the intercept of a line with a slope of one through each data point on such a plot. The intercepts themselves are plotted on the ordinate of Fig. 15. There are obviously several rocks with

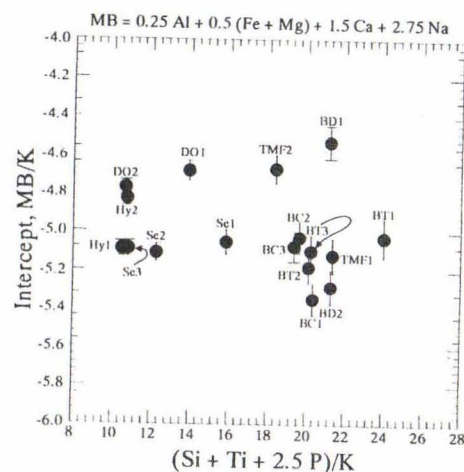


FIG. 15. Plot of the intercepts from lines with a slope of one drawn through each data point for the COM-A rocks on a plot of $(\text{Si} + \text{Ti} + 2.5 \text{ P})/\text{K}$ vs. $[0.25 \text{ Al} + 0.5(\text{Fe} + \text{Mg}) + 1.5 \text{ Ca} + 2.75 \text{ Na}]/\text{K}$. If all the rocks are drawn from a single magma batch, each data point should have the same intercept (i.e., the data points should fall on a horizontal line). The error bars show the $\pm \sigma$ uncertainty in the intercept owing to analytical uncertainties.

intercepts that are within analytical uncertainty of each other (BT1, TMF1, BT3, BC2, BC3, Se1, Se2, Hy1, and Se3). Just as obviously, there are others that do not share the same intercept (BD1, TMF2, DO1, DO2, Hy2, BC1, BD2, and possibly BT2). The rocks with the same intercept, within analytical uncertainty, probably form one magma batch (Nicholls & Russell, 1991) whereas the others either belong to different magma batches or have been

contaminated, suggesting processes of crystal sorting overprinted by contamination by pumiceous rhyolite as causes of the chemical diversity in the COM-A lava flows (Stout *et al.*, 1989). Contamination is also supported by Sr and Nd isotope contents (Leeman, 1982c; Futa *et al.*, 1988).

The chemical variations in the COM-A lava flows, reflected in the presence of several rock types (basalts, trachybasalts, tristanites, and trachytes), are evidence of one or more differentiation mechanisms. Chemical variations among rocks with the same intercepts (Fig. 15) cannot be explained by olivine and plagioclase alone but must include augite and Fe–Ti oxide accumulation as well (Stout *et al.*, 1989). Both Pearce element ratio plots and mass balance calculations indicate the involvement of pyroxene and Fe–Ti oxides. The amount of fractionation required to produce melts in equilibrium with Fa_{50} (trachybasalt stage, Fig. 8) exceeds 30%. This number compares with an inferred fractionation of more than 22% of the original mass to produce tholeiite basalts from picrites during the 1968 eruption of Kilauea volcano, Hawaii [calculated from data of Nicholls & Stout (1988)]. The distance between the vents that erupted the picrites and tholeiites was ~10 km.

Thermodynamic modeling suggests that olivine and plagioclase phenocrysts and microphe-nocrysts in COM-A rocks were not in equilibrium with enclosing melts at surface pressures. Pressure affects the order of mineral saturation and the ensuing order of crystallization (Fig. 14). A high-pressure sorting stage is consistent with indicators from chemical data that augite + Fe–Ti oxide phases participated in the derivation of COM-A rocks from a basaltic parent. The modeling also shows that augite could appear on the liquidus with plagioclase at high pressures (Fig. 14). The gaps in the compositional spectrum of COM-A lava flows (e.g., absence of rocks in the SiO_2 range 52–55% and the separated position of the Thompson space polyhedron for the trachyte; Fig. 5) suggest residence periods at depth to allow time for sorting and contamination processes to run to near-completion.

Euhedral zircon may either indicate contamination by country rocks or that the source rocks had higher than usual Zr concentration. The near-constant composition of olivine in the trachytes in habits of several sizes suggests either unusual fractionation conditions or special circumstances during contamination. Abundant brown apatite suggests that F and H_2O are factors that influenced the crystallization and differentiation processes. Finally, the paucity of pyroxene in the SRP basalts in general and in the COM lava flows in particular also suggests either unusual source rock compositions or special processes of formation. The Thompson space diagram (Fig. 5) illustrates that chemical compositional spaces exist where pyroxene will not crystallize (the $\text{Di}=0$ boundary).

It has been established (Stone, 1969; Leeman *et al.*, 1976; Stout & Nicholls, 1977; Leeman, 1982c; Menzies *et al.*, 1984; Kuntz *et al.*, 1985, 1986a) that the SRP and COM-A lava flows can be related to each other to a large extent by crystal sorting and some contamination by country rocks. Detailed petrology of the COM-A suite of rocks shows that petrogenetic processes and relationships between specific rocks are complex and warrant future study. The specific P – T ascent paths followed by individual magmas, the number of individual magma batches, relationships between magma batches, and the role of contaminants can perhaps be further constrained by delineating which rocks originate from separate magma batches, constraining possible differentiation sequences within and between these batches, and by more extensive thermodynamic modeling to predict coexisting mineral assemblages along different P – T paths.

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