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Contributions to
Mineralogy and
Petrology
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Evolved Lavas from the Snake River Plain: Craters of the Moon National Monument, Idaho

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Abstract. Holocene lavas from Craters of the Moon (COM) National Monument are representative of "differentiated" lavas which occur around the margins of the Snake River Plains (SRP) and they range serially in composition from alkali- and phosphorous-rich ferrobasalts to ferrolatites. Petrographic study indicates that these lavas evolved primarily by cotectic crystallization of olivine, plagioclase, magnetite and apatite in the mafic members of the suite (ferrobasalts), and by cotectic crystallization of plagioclase, magnetite, clinopyroxene and minor olivine in the salic members. Quantitative phase relations in the COM lavas, calculated by means of a least-squares mixing program, indicate that the observed range in composition among these lavas corresponds to at least 70 percent crystallization of a magma similar to the most mafic COM lavas. Anhydrous one-atmosphere experimental crystallization studies fail to reproduce exactly the inferred phase relations; the discrepancy is attributed to the presence of water in the naturally crystallized magmas. The origin of COM parental magma cannot be unequivocally resolved. Available evidence suggests that COM lavas do not represent melts derived directly from the mantle: (1) high $\text{Sr}^{87}/\text{Sr}^{86}$ ratios (0.708 to 0.712), (2) relatively high $\text{Fe}/(\text{Fe}+\text{Mg})$ and excluded-element content in even the most mafic COM lavas, (3) occurrence of megacrysts of inferred high-pressure origin in the Lava Creek flow. Megacrysts occur in the Lava Creek flow as clusters of labradorite, aluminous clinopyroxene, and olivine. Analogy with the experiments of Thompson [1] and least squares mixing calculations indicate that intermediate (ca. 8 to 10 Kbar) pressure fractionation of such megacrysts from olivine tholeiite magma may yield derivative COM-type liquids.

Introduction

Small volumes of evolved lavas of tholeiitic affinity occur sporadically along the margins of the Snake River Plain (SRP). These lavas have received little detailed study, although their occurrence has been noted near the town of King Hill [2, 3] on the west rim of island Park caldera [4] and at Craters

of the Moon National Monument [5, 6, 7]. The latter occurrence is the most extensive and well exposed and comprises a lava field which covers more than 300 square kilometers. For convenience, and to avoid genetic implications, all evolved lavas of the SRP are herein denoted as Craters of the Moon (COM)-type lavas; those from Craters of the Moon lava field proper are designated COM lavas. The ages of lavas vary from Pliocene (ca. 3 m.y. old) at King Hill to Holocene at Island Park and Craters of the Moon [8, 9]. COM-type lavas typically are enriched in iron, phosphorus, titanium, and alkalis compared to SRP olivine tholeiites [10, 11]. Compositionally they range from andesine-normative olivine ferrobasalt (44 to 51% SiO₂, 13 to 17% Fe as FeO, and up to 2.6% P₂O₅) to ferrolite (63% SiO₂, 8% Fe as FeO and 4 to 5% of both Na₂O and K₂O). Compositions of these rocks vary regularly with changes in such differentiation indices as Fe/(Fe+Mg) or MgO content. The rocks could be subdivided into numerous categories (e.g. tholeiitic basaltic andesite, tholeiitic andesite, etc.) but such nomenclature is somewhat arbitrary and is not adopted. The COM lavas are unique in many respects and existing classification schemes fail to represent them adequately.

Sr⁸⁷/Sr⁸⁶ ratios in COM-type lavas vary from 0.708 to 0.712 and are higher than those in SRP olivine tholeiites [12, 13, 14]. Correlations between Sr⁸⁷/Sr⁸⁶ and such compositional parameters as Rb/Sr, K₂O, and SiO₂ suggest that these lavas have been contaminated to some degree by crustal strontium. The occurrence of xenoliths and xenocrysts of crustal-derived rocks (mainly one- and two-pyroxene granulites and granitic rocks) in several lava flows at Craters of the Moon and at King Hill demonstrates some interaction between magma and crust.

Thompson [1] determined anhydrous liquidus phase relations in a specimen of King Hill basalt (sample OB-2) at 35 Kbar. However, his work left unresolved the question of a genetic link between the SRP olivine tholeiites and COM-basalts. Considerable enrichment of P₂O₅ and K₂O (up to 2.0 weight percent each) in the most mafic COM-type lavas (44 to 46% SiO₂) is difficult to explain in terms of either fractional crystallization or contamination hypotheses.

A detailed study of lavas from Craters of the Moon lava field was undertaken to help resolve the question of their origin and relation to SRP volcanism. This suite was selected for study because it comprises the most complete compositional range known for COM-type lavas and because flow relations and relative chronologies are well understood.

In this paper we present mainly chemical analyses of selected whole-rock samples and their constituent phenocrysts. These data are used to construct a crystal fractionation model that can account for the observed compositional range of the lavas within this suite. We also discuss possible origins for the COM lavas. Analytical methods used in this study are described elsewhere [11, 15].

Geology of Craters of the Moon National Monument Area

Descriptions of volcanic features and geologic mapping in the vicinity of Craters of the Moon National Monument have been published [5, 16, 17, 18]. The

Table 1. Summary of petrographic data for COM lavas

Analyzed flow units (sample nos.) ^a	Microphenocrysts ^b					Notes
	Oliv	Plag	Mt	Apat	Others	
<i>Phase One</i>						
Lava Creek flow (69-22, 70-42, V-32)	XX	A	X	SA	—	Contains sparse cpx-plag-oliv-mt megacryst clusters
Sunset Cone NE flow (SBR-4, 72-25)	XX	A	XX	X	—	
Sunset Cone W flow (CM-1)	XX	A	XX	X	—	
Sunset Cone NW flow (72-27)	XX	A	X	X	—	
Grassy Cone flow (V-28)	X	XX	X	SA	—	
<i>Phase Two</i>						
Highway flow (62B1, 69-31, V-26, V27)	TR	X	X	—	Cpx(SA)	Contains sparse partly resorbed anorthoclase and crustal xenoliths
Devils Orchard flow (69-19, 69-20, CM-2, V30, V-31)	SA	X	X	—	Cpx(SA)	Contains sparse partly resorbed anorthoclase and crustal xenoliths
Cinder cone at Monument Headquarters (N-3, N-4)	thin sections not examined					
Serrate flow (69-36, V-33)	SA	X	X	—	Cpx(SA)	Contains crustal xenoliths
<i>Phase Three</i>						
Big Craters NW flow (SBR-5, RUS)	X	XX	X	SA	—	
Big Craters SW flow (V-19, V-29)	X	X	X	SA	—	
Flow on NW margin of lava field (WPL-86, WPL-87)	X	XX	X	TR	—	
Little Prairie flow (N-1)	thin section not examined					
Indian Tunnel flow (CM-3)	thin section not examined					
Ejecta block, Yellowjacket waterhole (69-35)	—	X	—	—	—	Fine-grained, nearly equigranular, holocrystalline with plag, oliv, mt, apat, cpx.
North Crater flow (N-2, CM-4, NCRA, TACH)	X	X	X	—	—	
Rhyolitic ejecta blocks, North Crater (NCP-1, NCP-2R, NCP-2C, NCP-3)	—	X	SA	—	Qtz(X), Cpx(X)	NCP-1 contains biotite and sparse hypersthene
<i>Phase Four</i>						
Fissure basalt, Bearsden waterhole (69-33)	—	X	X	—	—	Contains crustal xenoliths
Big cinders NE flow (69-21)	X	XX	X	X	—	
Blue Dragon flow (BD-1, BD-S)	XX	A	X	SA	—	
Flow on SE margin of lava field (69-17)	XX	A	X	SA	—	
Fissure basalt, SE margin of lava field (69-28)	XX	A	—	TR	—	

^a Sample numbers are given for chemically analyzed rocks

^b Key: TR=trace amount (<0.2%), SA=small amount (<1%), X=1-5%, XX=5-10%.

lava field is situated along the northwest margin of the SRP where it abuts the Paleozoic sedimentary and early Cenozoic (Eocene?) Challis volcanic rocks of the Pioneer Mountains. Most of the vents in the lava field are aligned along segments of the north-northwest trending Idaho rift [19], a tensional feature which extends for a distance of some 50 km with a strike roughly parallel to that of Basin and Range type faults north and south of the SRP. These relationships suggest that the Idaho Rift may be the surficial expression of renewed basement faulting which served as a conduit for ascending Craters of the Moon lavas.

In the vicinity of the National Monument there are approximately 100 cinder cones (including two which occur in the Pioneer Mountains along the strike of the rift zone) and fissure vents and more than 50 lava flows. Murtaugh [18] distinguished four main eruptive episodes, but noted that activity was more or less continuous during the last three episodes. Armstrong and others [9] obtained "zero" m.y. K-Ar ages for two of the oldest flows and Bullard and Rylander [8] and Bullard [20] obtained C^{14} ages of about 2,000 years B.P. for younger flows in two areas of the COM lava field. Thus, it is probable that the entire eruptive sequence is no older than late Pleistocene.

Samples were collected from many of the major lava flows in the National Monument and from some of the outlying flows in the lava field. The flows studied are listed in Table 1 in approximate stratigraphic order.

Petrography

Flow interiors were exposed only in a few localities and as a result samples were generally collected near flow tops. Consequently, nearly all are very fine-grained or vitric with hyalopilitic or intersertal to intergranular textures. A correlation exists between the type of flow (i.e., pahoehoe, aa, or blocky) and mineralogy and bulk composition: The ferrobasalts grade from pahoehoe to aa as they become more enriched in SiO_2 and the ferrolatites are typically blocky flows, reflecting the relation between high SiO_2 and relatively higher viscosity in the liquid state.

The ferrobasalts contain seriate microphenocrysts and microlites of olivine, plagioclase, magnetite and apatite; the vitric to turbid residuum contains crystallites of the same minerals plus subhedral to acicular clinopyroxene. The groundmass commonly is nearly opaque owing to finely disseminated magnetite. Olivine and apatite are most abundant in the more mafic flows. For example, sample 72-27 contains (in volume percent): 15-20% plagioclase (up to 1.0 mm), 5-10% olivine (about 1-2% as phenocrysts up to 2 mm in maximum diameter), 5% magnetite (up to 1 mm), 2% apatite (up to 0.5 mm in length), and about 50% glassy mesostasis.

Apatite occurs as intergrowths with olivine or magnetite microphenocrysts and is considered to be a liquidus or near-liquidus phase based on its textural relationships. It also occurs as euhedral hexagonal prisms in the groundmass. Magnetite occurs as inclusions within olivine microphenocrysts, as distinct microphenocrysts, and as quench crystals which comprise chains or cruciform growths

of very small cubic grains. Plagioclase occurs as euhedral, occasionally skeletal, laths which are commonly flow-aligned. Sparse megacrysts of unzoned plagioclase (up to 1 cm in length) occur in glomeroporphyritic intergrowths with clinopyroxene (up to 5 mm maximum dimension) and olivine (up to 2 mm diameter) in sample 70-42. Aluminous magnetite is also found in these clusters as inclusions in olivine. These clusters display no obvious reaction relationship with the surrounding groundmass (i.e., no zoning, resorption, deformation, etc.), but the groundmass is glassier near the clusters. The most mafic ferrobasalt (69-28) contains no microphenocrysts of apatite, but does contain phenocrysts of olivine and plagioclase. The only other important phase observed is ilmenite which is found only in the groundmass of samples 69-28, 70-42, and 69-22. Rare grains of groundmass mica were found in some thin sections of the Lava Creek flow.

Olivine and apatite microphenocrysts are sparse or lacking in the ferrolatites (especially those more siliceous than sample 69-19). Plagioclase and magnetite are the dominant liquidus phases in these rocks. However, sparse tabular microphenocrysts of clinopyroxene are present in the most siliceous ferrolatites (e.g., 69-20, 69-31). Plagioclase, magnetite, skeletal olivine, and clinopyroxene microphenocrysts occur together in glassy residuum of sample 69-20 (Devils Orchard flow), suggesting that all of these minerals precipitated at near-liquidus temperatures. Some of the ferrolatites contain sparse partly-resorbed unzoned anorthoclase (up to several mm diameter) and sodic sanidine (up to 1 mm in length) as well as sodic plagioclase laths. The partly resorbed alkali feldspars commonly have narrow reaction rims of sodic plagioclase. Samples from the Highway flow contain sparse microphenocrysts of clinopyroxene and olivine. The fine-grained residuum of the ferrolatites typically contains light brown to turbid glass, prismatic microlites of clinopyroxene, olivine, rare orthopyroxene, and magnetite.

Pumiceous rhyolitic xenoliths from North Crater typically contain phenocrysts of plagioclase, sanidine, magnetite and in some cases, quartz and sparse clinopyroxene microphenocrysts in a vesicular glassy to cryptocrystalline matrix. One sample (NCP-1) contains biotite and sparse orthopyroxene in addition to clinopyroxene, two feldspars and magnetite.

Plutonic and metamorphic xenoliths, ranging in size from less than 1 cm up to 0.5 m in diameter, are found in some COM lavas, notably the Serrate and Devils Orchard flows. The overall volume of xenolithic material in this flow is much less than one percent. The xenoliths are dominantly one- or two-pyroxene granulites and two-feldspar-quartz $\pm$ biotite granitic rocks. They will be described in detail elsewhere. Evidence of reaction between xenoliths and host lava was not observed, but xenocrysts are most abundant in samples of lava collected near large xenoliths, suggesting that the xenoliths have been partly disaggregated. Usually the xenolith-lava contacts are sharp, but under the microscope it is obvious that tiny veinlets of lava have penetrated at least the margins of the xenoliths. In addition, a pale brown to clear glass is commonly found along intergranular contacts. It is suggested that this glass is formed by partial fusion of the xenoliths.

Petrographic data for the analyzed samples are summarized in Table 1. Approximate modes were estimated visually and checked in some cases by point counting. Most samples contain less than 10 to 15 percent total microphenocrysts.

Table 2. Compositional range of selected minerals in COM lavas*

Olivines					Plagioclases				
69-28	69-22	72-27	69.17		69-22	72-27	69-17	69-35	
OL28	OL22	OL27	OL17		PL22	PL27	PL17	PL35	
SiO ₂	35.9	35.4	34.7	33.3	SiO ₂	55.1	56.2	56.8	59.9
TiO ₂	0.07	0.08	0.05	0.02	TiO ₂	0.15	0.07	0.01	0.04
Al ₂ O ₃	0.23	0.30	0.11	0.13	Al ₂ O ₃	27.7	27.5	25.6	24.9
FeO	25.7	33.1	37.4	42.2	FeO	0.78	0.59	0.58	0.63
MnO	0.35	0.49	0.64	0.58	MgO	0.14	0.07	0.05	0.02
MgO	36.9	29.6	26.2	19.9	CaO	10.6	9.54	8.11	7.35
CaO	0.37	0.35	0.48	0.54	NaO	4.98	5.34	6.04	6.74
KO	—	—	—	—	KO	0.49	0.66	0.82	1.15
Total	99.6	99.4	99.6	96.7	Total	99.9	99.9	98.0	100.7
%Fo	72	61	57	46	%An	53	49	41	35
Magnetites					Pyroxene				
69-22	72-27				69-20	72-27			
MT22	MT27				CPX 20	APAT*			
SiO ₂	0.52	0.30			SiO ₂	47.5	0.41		
TiO ₂	24.7	23.5			TiO ₂	0.59	0.01		
Al ₂ O ₃	2.29	3.01			Al ₂ O ₃	1.81	0.02		
FeO	66.6	67.7			FeO	26.2	1.00		
MnO	0.77	0.59			MnO	0.44	0.01		
MgO	2.75	2.92			MgO	4.82	0.41		
CaO	0.26	0.13			CaO	18.1	54.7		
					Na ₂ O	0.48	—		
					P ₂ O ₅	—	41.0		
Total	97.9	98.2			Total	99.9	99.9		
Recalculated analyses					Total				
Fe ₂ O ₃	18.9	20.2			%Wo	40.0			
FeO	49.7	49.5			%En	14.8			
Total ^c	99.8	100.2			%Fs	45.2			
%Usp	60.5	60.8							
%Mt	23.1	26.0							
Others	16.4	13.2							

* Data by electron microprobe

* Cl not determined, total includes 3.92%F and is corrected for F=O₂

* Calculated assuming magnetite-ulvospinel stoichiometry

Mineralogy

The observed compositional ranges of olivine and plagioclase microphenocrysts throughout the COM suite are Fo₇₂ to Fo₅ and An₆₃ to An₃₀, respectively. Phenocryst-groundmass compositional ranges for these minerals in individual rocks are shown in Figure 5. Zoning in olivine and plagioclase phenocrysts is typically less than five mole percent of Fo and An respectively. Titanomagnetite microphenocrysts typically contain about 60 percent ulvospinel component throughout the suite, but MgO content decreases systematically in going from the mafic to silicic lavas. Other minor elements in the magnetites display no systematic trends in composition. Apatite microphenocrysts analysed in three COM ferrobasalts are similar in composition. Clinopyroxene microphenocrysts in the ferrolatites range in composition from ferroaugite to magnesian hedenbergite. Representative analyses of olivine, plagioclase, magnetite, apatite, and clinopyroxene phenocrysts are given in Table 2. More detailed descriptions of these minerals and the megacrysts in the Lava Creek flow are given in Leeman [15].

Table 3. Glass and groundmass compositions in craters of the moon lavas

	69-28	69-22	72-27	69-21	BD-1	69-17	69-19	69-20	V31	NCP-1
	GM	GM	GM	GM	GL	GL	GM	GL	GL	GL
SiO ₂	46.9	49.3	49.0	50.5	51.9	55.9	59.8	62.9	65.3	70.5
TiO ₂	3.46	3.44	3.29	3.26	2.73	1.53	0.60	0.55	0.55	0.37
Al ₂ O ₃	14.3	13.4	13.8	12.4	13.0	13.0	13.9	14.3	13.1	14.2
FeO*	13.1	13.25	15.1	14.1	15.0	9.34	8.40	8.79	7.92	0.43
MnO	0.21	0.17	0.26	0.28	0.29	0.17	0.10	0.15	0.18	0.00
MgO	3.73	3.31	2.76	1.99	2.74	0.83	0.31	0.25	0.19	0.04
CaO	9.91	8.89	7.33	7.69	6.74	5.87	3.96	3.26	2.82	1.31
Na ₂ O	3.58	4.38	4.21	3.99	3.80	4.01	4.75	4.32	3.33	2.53
K ₂ O	1.36	1.70	2.44	2.35	2.17	4.06	4.38	4.48	5.22	6.65
P ₂ O ₅	2.20	2.60	2.40	2.42	1.71	1.10	0.68	0.15	0.11	0.05
Total	98.8	100.5	100.5	99.0	100.0	95.7	96.8	99.1	98.6	96.0
Fe/(Fe+Mg)	0.781	0.802	0.849	0.880	0.848	0.919	0.946	0.973	0.977	0.912
Molecular norms (Fe3/Fe2=0.15)										
AP	4.77	5.52	5.11	5.26	3.68	2.44	1.50	0.32	0.24	0.10
IL	4.99	4.87	4.67	4.72	3.92	2.26	0.88	0.78	0.79	0.54
MT	2.06	2.04	2.33	2.22	2.34	1.50	0.86	1.36	1.24	0.07
OR	8.32	10.20	14.69	14.44	13.20	25.47	21.07	27.04	31.93	41.41
AB	33.31	39.96	38.52	37.27	35.12	38.24	45.00	39.63	30.96	24.29
AN	19.62	12.10	11.72	9.49	12.36	5.68	12.78	6.43	5.49	6.68
QZ	—	—	—	1.13	1.67	4.65	9.42	9.52	15.97	26.32
DI	13.15	12.36	7.49	11.00	8.45	14.10	2.61	7.28	6.60	—
HY	6.08	5.89	4.18	14.47	19.26	5.67	5.88	7.63	6.78	0.14
OL	7.71	7.04	11.29	—	—	—	—	—	—	—
COR	—	—	—	—	—	—	—	—	—	0.46

* Total iron as FeO

Residual Mesostatis

Analyses and molecular norms of residual glasses or fine-grained groundmass in nine lavas and one pumice xenolith are given in Table 3. These analyses display increasing $Fe/(Fe+Mg)$ and normative Or which parallel trends of increasing Fa in olivines and Ab in plagioclases from the respective samples. MgO , CaO , TiO_2 , and P_2O_5 decrease monotonically with increasing SiO_2 content in accordance with removal of observed phenocryst phases.

Major and Trace Element Compositions

Chemical analyses and molecular norms for 17 representative whole rock samples of lavas from COM lava field are presented in Table 4. Analyses of all 39 analyzed samples are available from the authors upon request. Major element compositions range serially from ferrobasic lavas with low SiO_2 and relatively high TiO_2 , FeO^* (total iron), P_2O_5 , and K_2O to ferrolatitic lavas with moderately high SiO_2 and FeO^* , high K_2O and Na_2O (with $K_2O/Na_2O=1.0$ to 1.2), and low MgO , TiO_2 and P_2O_5 . Al_2O_3 content varies little throughout this sequence, as is characteristic of many tholeiitic suites. Trace elements show variations in abundance that are sympathetic with the major element trends—e.g., concentrations of the included elements Ni, Cr and Co decrease with increasing SiO_2 content (Cr and Ni are essentially depleted in all samples with more than 49 percent SiO_2) while those of the excluded elements increase throughout most of the sequence.

Several features of the COM suite are notable. In particular, the content of P_2O_5 in the most mafic COM lavas is about five to ten times that observed in most tholeiitic lavas. Some alkalic lavas (mugearites, hawaiites and nephelinites) from Hawaii [21] contain as much P_2O_5 as COM lavas, but these rocks do not display comparable enrichment in iron and their K_2O/Na_2O ratios (<0.5) are distinctly lower. Similarly, some differentiates of tholeiitic liquids (e.g. filter-pressed ooze from Alae lava lake [22]) are relatively enriched in P_2O_5 , alkalis, and iron, but not to the extent of COM mafic lavas. The occurrence of basaltic lavas similar to those at COM have been documented only for other localities along margins of the SRP [2, 3, 4, 6]. Compared with typical SRP olivine tholeiites the mafic COM lavas are markedly enriched in alkalis, P_2O_5 , iron, and large-ion lithophile elements such as Zr, Ba and REE.

In an AFM diagram (Fig. 1) compositions of COM lavas define a coherent iron-enrichment trend coupled with strong enrichment of alkalis (with K_2O/Na_2O increasing progressively). Groundmasses and residual glasses from these samples define the same trend indicating that the whole rock samples lie essentially on a liquid line-of-descent.

Also shown in Figure 1 are projected compositions of a wide variety of materials that may underlie the COM area. These include crustal xenoliths and pumice ejecta from COM (see Tables 4 and 5), a quartz-monzonite from the north margin of the SRP, SRP rhyolites, Precambrian metasediments of the Albion Range, south-central Idaho, and estimates of average crustal compo-

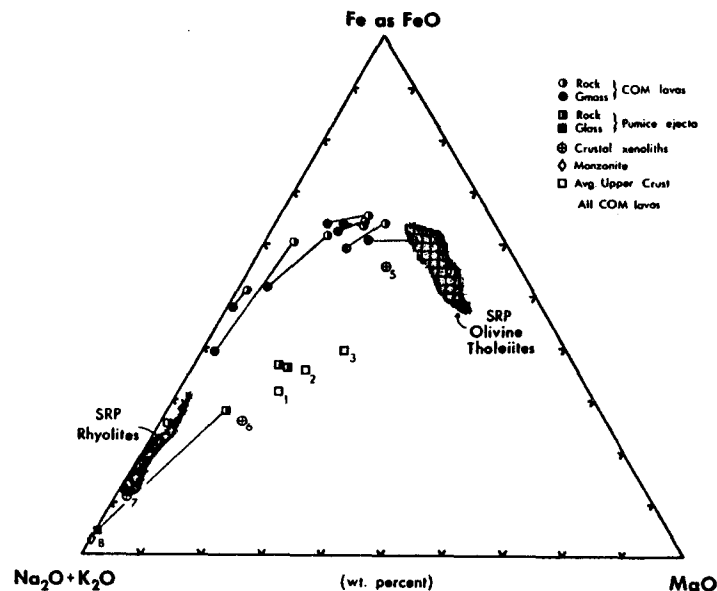


Fig. 1. AFM diagram showing range in composition of COM samples. SRP olivine tholeiites and SRP "Idavada" rhyolites. Tie-lines connect whole rock and glass compositions from the same rock. Also shown are compositions of xenoliths from COM lava field, a monzonite outlier of the Idaho Batholith, and estimated upper crust compositions; these points are keyed to analyses in Table 5.

sition (Table 5). These rocks all lie well off the COM trend indicating that addition of such material to any SRP or COM lavas cannot be responsible for the COM trend. On the basis of trace element data for these rocks (Table 5), it can be argued that the compositions of the COM lavas cannot be obtained simply by admixture of any of the analyzed crustal rocks with more primitive basaltic magmas such as the SRP olivine tholeiites. In fact, some trace elements (notably Hf, Zr, Ba, Th) are enriched in silicic COM lavas in concentrations much greater than found in any typical crustal rock.

Variation diagrams (Fig. 2) show decreases in TiO_2 , FeO^* , CaO , P_2O_5 , and included trace elements, and increases in SiO_2 , Al_2O_3 , Na_2O , K_2O and excluded trace elements with decreasing MgO . All of the variation trends are regular except those for Zr and Hf (not shown). These two elements are markedly enriched in the most mafic ferrolatites (CM-2 and 69-19) and become progressively depleted in the more silicic ferrolatites as Mg decreases. Zr/Hf ratios (44 to 55) remain roughly constant throughout the suite indicating that discontinuities in the variation trends for each of these elements are caused by the same mechanism. K/Rb (380 to 440) and K/Ba (12 to 15) ratios also vary little throughout the suite, whereas Rb/Sr (0.09 to 1.55) and Ba/Sr (2.5 to 27.6)

Table 4. Craters of the moon lavas

	69-28	69-22	WPL-87	SBR-4	CM-1	72-27	69-21	SBR-5
SiO ₂	45.1	44.4	45.7	45.9	46.04	46.7	48.7	51.5
TiO ₂	3.21	4.03	3.31	3.45	3.11	3.27	3.18	2.56
Al ₂ O ₃	14.3	13.3	13.9	13.3	13.91	13.6	12.8	13.5
Fe ₂ O ₃	0.15	—	—	—	2.76	—	—	—
FeO	15.1	17.12	16.9	17.5	13.91	16.3	16.5	15.0
MnO	0.27	0.30	0.31	0.31	0.30	0.30	0.30	0.28
MgO	6.26	4.90	4.01	4.16	3.89	3.97	3.74	2.79
CaO	9.55	8.53	7.69	7.68	7.45	7.56	7.59	6.58
Na ₂ O	2.55	3.34	3.46	3.52	3.45	3.39	3.19	3.76
K ₂ O	1.21	1.59	2.05	1.94	1.88	2.08	1.94	2.34
P ₂ O ₅	2.08	2.48	2.51	2.44	2.28	2.41	2.13	1.65
H ₂ O ⁺	0.20	—	—	—	0.74	—	—	—
H ₂ O ⁻	0.09	—	—	—	0.13	—	—	—
CO ₂	0.05	—	—	—	0.02	—	—	—
Total	100.1	100.0	99.7	100.1	99.87	99.6	100.0	100.0
Fe/(Fe + Mg)	0.712	0.780	0.811	0.810	0.815	0.807	0.818	0.845
Molecular norms (Fe ₃ /Fe ₂ = 0.15)								
AP	4.47	5.35	5.56	5.26	4.95	5.21	4.61	3.55
IL	4.59	5.79	4.74	4.96	4.50	4.71	4.58	3.67
MT	2.36	2.68	2.63	2.73	2.66	2.56	2.58	2.33
OR	7.34	9.68	12.45	11.57	11.54	12.71	11.86	14.21
AB	23.52	30.92	33.80	32.59	32.18	31.49	29.64	34.72
AN	24.65	17.06	15.77	15.23	17.58	16.35	15.40	13.42
QZ	—	—	—	—	—	—	—	0.60
DI	8.05	7.89	4.85	6.10	4.28	4.93	7.34	7.25
HY	13.10	2.44	1.78	5.84	8.76	11.14	23.49	20.26
OL	11.93	18.19	18.41	15.72	13.55	10.89	0.50	—
COR	—	—	—	—	—	—	—	—
Trace element abundances								
Ni	59.0	10.0	6.0	6.0	5.0	7.0	11.0	—
Co	48.0	42.0	35.0	36.0	35.0	36.0	36.0	33.0
Sc	29.0	24.0	26.0	23.0	24.0	24.0	27.0	28.0
Cr	65.0	16.0	14.0	11.0	4.0	5.0	3.0	—
Ba	700.0	980.0	1,100.0	1,180.0	1,230.0	1,170.0	1,210.0	1,360.0
Sr	274.0	330.0	315.0	317.0	319.0	326.0	291.0	285.0
Rb	24.0	30.0	41.0	41.0	39.0	41.0	39.0	48.0
Cs	0.27	0.34	—	0.6	—	0.48	—	—
Ta	4.1	6.0	6.5	8.4	6.6	6.5	6.3	15.0
Hf	11.5	16.0	23.0	21.0	20.0	20.0	18.0	24.0
Zr	626.0	857.0	1,063.0	1,060.0	1,067.0	1,051.0	968.0	1,180.0
Th	2.6	3.8	5.3	5.0	5.4	5.2	5.3	6.6
La	66.0	85.0	98.0	104.0	100.0	101.0	102.0	113.0
Ce	143.0	182.0	224.0	218.0	203.0	212.0	208.0	253.0
Sm	17.2	22.5	23.0	24.9	22.9	25.0	23.2	28.9
Eu	5.3	6.6	7.6	7.7	7.0	7.1	6.6	7.5
Tb	2.2	2.85	3.8	3.16	3.0	3.2	2.9	3.8
Yb	6.5	8.3	9.4	9.46	9.13	9.4	9.0	9.8
Lu	1.11	1.36	1.58	1.60	1.53	1.56	1.51	1.57
Sr ⁸⁷ /Sr ⁸⁶	0.7079	0.7081	0.7090	0.7098	—	—	—	0.7101

69-17	69-35	CM-2	69-19	69-20	V-31	V-27	NCP-1	NCP-3
52.1	56.9	56.8	58.1	62.1	62.6	63.5	63.3	72.2
2.23	1.30	1.29	1.30	0.77	0.73	0.48	0.64	0.44
14.4	15.3	14.5	14.4	14.8	14.8	14.4	16.4	12.0
—	—	2.39	—	—	1.79	1.14	—	—
14.3	10.7	10.6	12.3	9.28	7.45	7.14	3.69	2.82
0.26	0.22	0.25	0.24	0.23	0.20	0.19	0.06	0.01
2.33	1.61	1.12	1.02	0.41	0.35	0.30	1.29	0.13
5.98	4.92	4.56	4.38	3.20	3.19	2.91	3.42	0.85
4.29	4.58	4.02	3.65	4.55	4.05	4.11	3.16	2.87
2.70	3.35	3.32	3.63	4.50	4.67	4.81	5.12	5.16
1.40	1.00	0.63	0.62	0.25	0.19	0.09	0.24	0.06
—	—	0.15	—	—	0.18	0.07	—	—
—	—	0.03	—	—	0.01	0.04	—	—
—	—	0.01	—	—	0.06	0.01	—	—
100.0	99.6	99.7	99.7	100.0	100.3	99.2	97.3	—
0.860	0.872	0.923	0.925	0.959	0.964	0.966	0.744	0.956
2.93	2.11	1.35	1.33	0.53	0.40	0.19	0.51	0.14
3.17	1.83	1.85	1.86	1.08	1.03	0.69	0.92	0.64
2.23	1.65	2.04	1.92	1.42	1.40	1.32	0.58	0.45
16.14	20.00	20.15	22.05	26.87	28.02	29.14	31.19	32.17
37.77	41.46	37.08	33.69	41.30	36.94	35.27	29.23	27.16
12.29	11.53	12.06	12.53	6.61	8.74	8.10	15.93	4.03
—	2.18	4.19	7.17	6.95	9.31	11.57	14.07	31.61
7.26	5.23	5.56	4.52	6.24	4.86	4.89	—	—
16.69	13.92	15.72	14.93	9.00	9.30	8.84	7.57	3.47
1.53	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	0.01	0.32
—	—	—	—	—	—	—	—	—
29.0	15.0	12.0	11.0	—	2.0	0.5	7.0	2.0
26.0	22.0	27.0	25.0	24.0	20.0	17.0	8.0	5.0
—	—	—	—	—	—	—	—	—
1,680.0	1,830.0	2,010.0	2,100.0	3,100.0	3,260.0	3,200.0	1,960.0	1,350.0
282.0	259.0	228.0	217.0	184.0	175.0	116.0	—	—
55.0	71.0	76.0	79.0	94.0	97.0	104.0	184.0	—
—	—	0.9	0.95	1.5	1.5	1.3	7.1	2.3
20.0	23.0	8.5	8.6	27.0	9.6	22.0	1.6	3.7
28.0	33.0	45.0	42.0	41.0	37.0	36.0	6.4	13.4
1,300.0	1,620.0	2,500.0	2,250.0	1,840.0	1,830.0	1,572.0	310.0	610.0
7.3	9.0	10.0	10.0	13.0	—	15.0	18.0	28.0
124.0	134.0	131.0	134.0	150.0	154.0	166.0	49.5	75.5
257.0	264.0	272.0	274.0	292.0	298.0	330.0	88.0	154.0
29.0	29.9	25.0	26.2	32.0	32.0	35.0	7.2	14.2
7.6	7.7	7.0	7.2	8.1	8.2	7.54	1.8	1.77
3.5	3.8	3.3	3.3	4.2	4.0	4.4	0.65	2.6
10.7	11.5	12.4	12.6	13.0	13.0	13.5	2.1	10.0
1.83	1.94	2.11	2.08	2.24	2.2	2.38	0.4	1.77
0.7104	0.7124	—	0.7107	0.7108	0.7111	0.7117	—	—

Table 5. Compositions of selected crustal rocks

	1	2	3	4	5	6	7	8	9	10
SiO ₂	64.9	61.2	60.3	74.6	67.4	69.1	70.1	72.5	66.6	62.4
TiO ₂	0.5	0.6	1.0	0.4	1.03	0.29	0.09	0.01	0.26	0.76
Al ₂ O ₃	14.6	16.4	15.6	12.8	10.9	15.8	16.1	14.4	17.4	17.1
FeO	4.1	5.6	6.5	2.3	10.2	2.59	1.05	0.36	2.61	8.31
MnO	0.07	0.1	0.1	0.2	0.13	0.06	—	—	0.03	0.12
MgO	2.2	3.0	3.9	0.5	4.09	1.39	0.23	0.01	0.55	4.52
CaO	4.1	4.4	5.8	3.4	1.68	4.32	2.89	0.82	1.43	1.93
Na ₂ O	3.5	4.0	3.5	4.0	3.00	3.63	5.20	4.18	3.41	2.27
K ₂ O	3.1	3.0	2.5	4.4	1.03	2.63	2.42	6.36	5.90	2.37
P ₂ O ₅	0.15	0.16	—	0.3	0.03	0.16	0.10	0.09	0.12	0.17
Co	—	—	—	2.0	—	—	—	—	3.5	19.0
Sc	—	—	—	5.0	21.0	3.0	2.0	1.0	4.0	18.0
Cr	—	—	—	7.0	5.0	16.0	1.0	1.0	22.0	273.0
Ba	1,070.0	1,162.0	425.0	1,100.0	1,230.0	680.0	1,360.0	68.0	1,180.0	450.0
Sr	340.0	572.0	375.0	59.0	325.0	235.0	70.0	42.0	149.0	115.0
Rb	118.0	56.0	90.0	167.0	22.0	30.0	6.0	165.0	236.0	114.0
Hf	—	—	—	13.0	12.0	6.0	4.0	4.0	8.0	4.0
Zr	400.0	144.0	165.0	—	—	—	—	—	—	—
Th	10.3	5.1	9.6	28.0	33.0	0.1	6.1	49.0	62.0	9.0
Pb	—	15.1	12.5	—	9.0	15.8	22.4	30.0	—	—
La	—	—	—	78.0	101.0	22.0	29.0	25.0	96.0	21.0
Ce	—	—	—	161.0	230.0	32.0	49.0	52.0	192.0	42.0
Sm	—	—	—	14.0	13.0	0.78	1.2	3.6	11.9	4.3
Eu	—	—	—	1.7	3.0	0.96	0.95	0.35	0.82	0.9
Tb	—	—	—	2.0	1.5	—	0.10	0.71	1.13	0.6
Yb	—	—	—	5.8	4.2	0.43	0.20	1.6	1.08	1.9
Lu	—	—	—	1.0	0.8	—	0.04	0.4	0.28	0.37
K/Rb	218.0	445.0	232.0	218.0	389.0	728.0	3,350.0	320.0	208.0	173.0
K/Ba	24.0	22.0	49.0	33.0	7.0	32.0	15.0	776.0	41.0	44.0
Rb/Sr	0.35	0.12	0.24	2.84	0.07	0.13	0.09	3.93	1.58	1.00

- 1 Avg. Canadian Shield of Shaw and others, [31]
- 2 Avg. Lofoten banded granulite, [31]
- 3 Avg. crust of Taylor, [31]
- 4 Avg. SRP silicic volcanics (Leeman, unpublished data)
- 5-7 Xenoliths from COM lava field (#'s SI-1, CKI-1, 70-40, respectively)
- 8 Quartz monzonite, north margin of SRP (#70-14), (Leeman, unpublished data)
- 9 Avg. biotite gneiss, Precambrian Green Creek complex, Albion Range, south margin of SRP (#'s YAG-798, -800, -822), [32]
- 10 Biotite-oligoclase-quartz schist, Green Creek complex (# YAG-799), [32]

ratios increase progressively with increasing K₂O. A trend not commonly observed in differentiated lava suites is the strong depletion of P₂O₅ with concomitant enrichment of La and other REE as K₂O increases. It is shown below that these trends in composition can be explained in terms of fractionation of observed phenocryst phases.

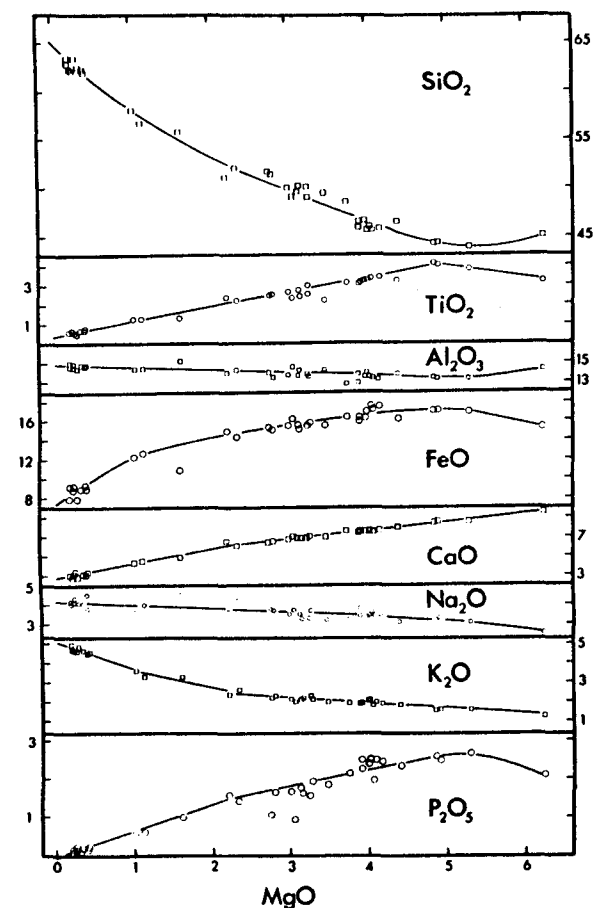


Fig. 2. MgO-variation diagram showing major-element compositional variations in COM lavas

Phase Relations and Experimental Studies

Compositional variations within the COM lavas are reflected in their molecular norms. The mafic ferrobases all contain normative olivine and hypersthene, whereas the silicic ferrobases and ferrolites contain normative quartz and hypersthene. Approximate phase relations for this suite may be inferred through use of the pseudoquaternary basalt-tetrahedron of Yoder and Tilley [23]. Figure 3 shows the normative compositions of COM lavas projected from olivine and plagioclase. Compositional trends defined by the ferrobases and their

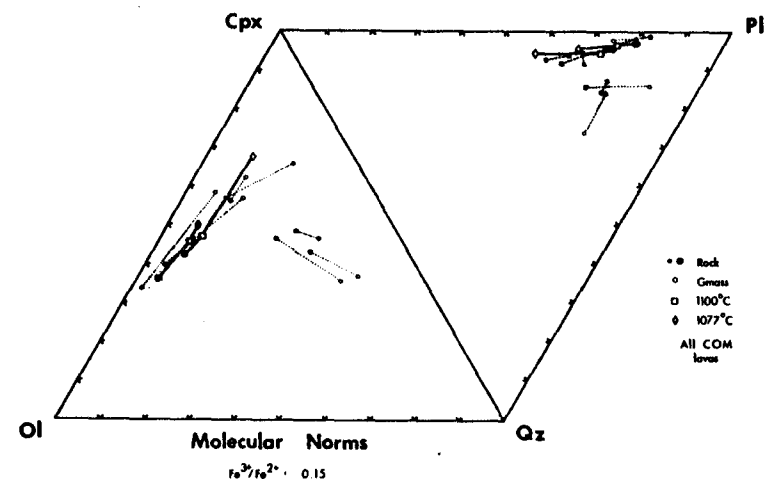


Fig. 3. Analyses of COM lavas projected into normative basalt-tetrahedron. Stippled area shows range of all whole-rock analyses. Tie-lines connect whole-rock and groundmass (or glass) compositions from the same rock. Squares and diamonds denote glasses formed by crystallization of two ferrobasalts at a pressure of one atmosphere (see Table 6)

residual groundmasses are compatible with dominant olivine and plagioclase fractionation. The ferrolites and their groundmasses define a separate trend at a high angle to the ferrobalt trend which is compatible with dominant olivine and plagioclase fractionation. The ferrolites and their groundmasses define a separate trend at a high angle to the ferrobalt trend which is compatible with entry of clinopyroxene as a liquidus phase.

Phase relations in the projection from olivine are less clearly displayed but are also compatible with cotectic plagioclase and olivine fractionation in the ferrobalt followed by dominant clinopyroxene-plagioclase control for ferrolites. It is clear that these projections do not completely represent the COM bulk compositions since there are no fields for magnetite or apatite which are inferred to be cotectic phases with olivine and plagioclase.

The crystallization behavior of two COM ferrobalt was experimentally studied under conditions of controlled oxygen fugacity and one atm total pressure. Previous studies [7, 24] have shown that the order of phases crystallizing from COM lavas is strongly dependent upon values of oxygen fugacity. However, they were unable to reproduce the naturally occurring near-liquidus mineral assemblages in these rocks under anhydrous conditions, and suggested that COM lavas crystallized under water-undersaturated conditions. With these limitations in mind, our experiments were run near the synthetic QFM buffer, under which condition olivine, plagioclase and ilmenite crystallized within about 20° to 30° C of the liquidus in compositions 70-42 and 72-27. Glasses and selected minerals from four of these runs were analyzed using an electron micro-

Table 6. Analyses of products from experimental runs at pressure = 1 Bar

	70-42, 1,100°C, QFM			70-42, 1,077°C, QFM			72-27, 1,100°C, QFM			72-27, 1,077°C, QFM	
	Glass	Plag	Oliv	Glass	Plag	Oliv	Oxide	Glass	Plag	Oxide	Glass
SiO ₂	45.5	54.4	36.6	44.1	55.6	35.7	0.10	47.4	54.9	0.32	51.0
TiO ₂	4.19	0.19	0.10	4.33	0.15	0.09	53.5	3.45	0.18	53.2	2.95
Al ₂ O ₃	13.9	28.5	0.07	11.2	27.6	0.09	0.34	13.9	28.1	0.32	11.7
FeO	14.7	0.62	32.7	17.6	0.43	31.0	41.5	14.5	0.67	39.8	15.5
MnO	0.32	—	0.58	0.37	—	0.72	0.56	0.33	—	0.65	0.32
MgO	4.74	0.14	31.4	3.75	0.07	25.8	4.42	4.24	0.10	4.41	1.99
CaO	8.70	11.0	0.37	9.89	9.63	0.54	0.29	7.95	10.4	0.60	8.01
Na ₂ O	3.37	5.08	—	3.12	5.65	—	—	3.53	5.13	—	3.33
K ₂ O	1.55	0.51	—	2.02	0.95	—	—	1.88	0.81	—	3.13
P ₂ O ₅	2.64	—	—	4.16	—	—	—	2.62	—	—	1.93
Cr ₂ O ₃	—	—	—	—	—	—	0.24	—	—	0.18	—
Sum	99.6	100.5	101.7	100.5	100.1	101.9	100.9	99.8	100.2	99.5	99.9
Fe/ (Fe + Mg)	0.755	—	—	0.824	—	—	—	0.774	—	—	0.888

Molecular norms (Fe ³⁺ /Fe ²⁺ = 0.15)				
AP	5.69	—	9.04	5.63
IL	6.02	—	6.27	4.94
MT	2.29	—	2.77	2.26
OR	9.44	—	12.40	11.41
AB	31.21	—	29.10	32.56
AN	18.77	—	11.03	17.04
DI	6.37	—	9.37	4.72
HY	9.91	—	10.67	14.39
OL	10.31	—	9.36	7.07
OZ	—	—	—	—
mole% An	—	52.8	—	45.9
mole% Fo	—	—	63.1	—

probe and the results are presented in Table 6. In the experiments with 70-42 olivine (Fo₆₃) and plagioclase (An₅₃) were the only phases to crystallize at 1,100°C; their compositions are identical to those of microphenocrysts in the actual rock. At 1,077°C ilmenite had joined olivine (Fo₅₄) and plagioclase (An₄₆), but magnetite failed to crystallize in any of the runs near QFM as was observed by Thompson [24]. With composition 72-27 a similar crystallization sequence was observed but the liquidus plagioclase at 1,100°C was more sodic (An₅₀). Apatite was not observed in any run. It is clear that our experiments have not reproduced the natural crystallization behavior of COM ferrobalt. Thompson [24] showed that crystallization of magnetite in these rocks was critically dependent on the prevailing oxygen fugacity, requiring values close to the NNO buffer under anhydrous conditions. We conclude that the discrepancies between the experimental and natural crystallization behavior of COM

lavas may be attributed to the role of water in the natural system. The presence of water in crystallizing silicate melts tends to reduce the liquidus temperature of plagioclase relative to that of other silicate and oxide phases [25] and may favor higher oxygen fugacities. The latter effect would increase the activity of Fe^{3+} in the liquid, favoring precipitation of magnetite over ilmenite. The absence of apatite in the experimental runs is not so easily rationalized, but may also be related to the anhydrous nature of the experiments since apatites generally contain OH^- radicals in their structure.

Empirically Derived Fractionation Model

An empirical method has been used to evaluate the phase relations that obtained in the natural COM liquids. Accumulated evidence suggests that the COM lavas are genetically related through fractional crystallization of a series of magmas of common parentage. The chemical evolution of these lavas cannot be a simple process since the eruptive sequence does not correspond directly with compositional changes. For example, the first eruptive phase includes the most mafic lavas (Lava Creek, Sunset Cone, and Grassy Cone flows), with exception of 69-28 which was collected from one of the youngest flows (see Table 1). The second phase includes the most silicic lavas (Devils Orchard, Serrate and Highway flows), and subsequent eruptive phases reverted back to more mafic compositions. It must be remembered that all of these phases occupied a relatively short time-span, during which batches of magma of different compositions probably coexisted in different reservoirs.

If it is assumed that the same differentiation processes operated on each discrete batch of magma and that the extent of such differentiation was proportional to residence time in some subsurface reservoir prior to eruption, it can be postulated that the erupted lavas provide a sampling of compositions along the liquid line of descent of the parental magma. This model was employed to estimate the proportions of phases that must be removed to obtain derivative liquids corresponding to observed compositions of COM lavas.

A least-squares mixing program [26] was used to determine optimum compositions and proportions of phenocrysts that must be removed to derive successive COM lavas from an assumed parental liquid equivalent in composition to sample 69-22 (Lava Creek flow). This sample was chosen as the parent because it is one of the earliest flows and also has the features of being the most mafic (i.e., highest concentrations of included trace elements, lowest $\text{Fe}/(\text{Fe}+\text{Mg})$, etc.) lava in the sequence (with exception of 69-28). The Lava Creek flow has a microphenocryst assemblage which, with exception of rare megacrysts, closely resembles that in other more evolved ferrobasalts. Sample 69-28 was rejected as a hypothetical parent both because it is one of the youngest lavas and its phenocryst assemblage and composition do not closely correspond to other COM lavas. We do not necessarily imply that 69-22 is itself a primary liquid (derived by direct partial melting of the mantle), but only that it may serve as a reference point along the liquid line of descent of the COM parental magma.

Table 7. Representative cumulative fractionation models

Mix	69-22 to:	F	X_{OL}	X_{PL}	X_{MT}	X_{AP}	X_{PX}	Σr_i^2
1	SBR-4	0.7707	0.0412	0.1302	0.0486	0.0165	—	2.320
2	CM-1	0.7957	0.0433	0.1043	0.0567	0.0189	—	1.924
3	72-27	0.7546	0.0462	0.1302	0.0596	0.0186	—	1.071
4	69-21	0.7042	0.0540	0.1564	0.0683	0.0247	—	0.724
5	SBR-5	0.6485	0.0757	0.1384	0.0905	0.0384	—	3.017
6	69-17	0.5563	0.0870	0.2116	0.1086	0.0446	—	1.110
7	69-35	0.4646	0.1018	0.2465	0.1378	0.0532	—	1.904
8	CM-2	0.4458	0.1071	0.2687	0.1342	0.0566	—	1.839
9	69-19	0.4181	0.1092	0.2878	0.1377	0.0570	—	1.632
10	69-20	0.3427	0.1088	0.2971	0.1472	0.0585	0.0546	0.488
11	V-31	0.3332	0.1098	0.3069	0.1487	0.0588	0.0517	0.695
12	V-30	0.3425	0.1099	0.3054	0.1493	0.0594	0.0453	0.774
13	V-27	0.3200	0.1103	0.3195	0.1528	0.0596	0.0493	0.731
14	69-28 to 69-22	0.7662	0.0694	0.1472	—	0.0068	—	1.57 ^a

Notes:

Mineral compositions used are as follows: OL28($\text{Fe}_{0.2}$), PL22(An_{53}), MT22, APAT, and in mixes 10-13, PX20

Mixes were weighted according to analytical errors for each component as follows: Si: 1%; Ti, Al, Fe, Mg, Ca: 2%; Na, P: 3%; K: 5%; Mn: 10%

Table 8. Representative incremental fractionation models

Step ^a	F	X_{OL}	X_{PL}	X_{MT}	X_{APAT}	Σr_i^2	Minerals fractionated
69-22 to 72-27	0.7546	0.0462	0.1302	0.0596	0.0186	1.071	OL28, PL22, MT22, AP
69-22 to 69-21	0.7042	0.0540	0.1564	0.0683	0.0247	0.724	OL28, PL22, MT22, AP
72-27 to 69-17	0.7192	0.0548	0.1198	0.0696	0.0356	0.179	OL28, PL27, MT27, AP
72-27 to 69-35	0.6086	0.0727	0.1591	0.1073	0.0471	0.872	OL28, PL27, MT27, AP
69-35 to 69-20	0.7277	0.0435	0.1823	0.0325	0.0200	0.071	OL22, PL17, MT35, AP
69-35 to V-31	0.6702	0.0517	0.2238	0.0353	0.0211	0.214	OL22, PL17, MT35, AP
69-35 to V-27	0.5940	0.0697	0.2799	0.0461	0.0226	0.577	OL22, PL17, MT35, AP

^a Each step is calculated assuming that first sample is parent and second sample is derivative. F is fraction of parent remaining after each step. X_i is fraction of parent that crystallizes as mineral i during each step.

In constructing a fractionation model it was assumed that phenocrysts were removed from a liquid A to produce a derivative liquid which is equivalent to a more evolved lava, B. The calculations were performed by assuming that proportions of derived liquid B and removed microphenocrysts sum up to the composition of A such that the squares of the differences for each oxide component between calculated and observed A are minimized. The "goodness of fit" for each calculation is expressed as the sum of the squared residuals (r_i =difference between calculated and observed values for each component i).

Thus, small values of Σr_i^2 indicate a good mathematical solution. The mixing calculations were performed after weighting each component according to the analytical uncertainty associated with its determination. This insures that poorly determined elements receive the least weight, while those which are well determined receive proportionately greater weight.

Input data consisted of chemical analyses of the rocks A (=69-22) and B and the microphenocryst phases. In all cases the mineral compositions used were determined by microprobe analysis of phenocrysts in the COM lavas [15]. It cannot always be assumed that microphenocrysts in A are those which were removed to obtain B. In the case of relatively dense minerals, such as olivine, it was assumed that the microphenocrysts actually removed were slightly more Fo-rich than those observed. For each mixing model a range of mineral compositions selected from analyzed COM phenocrysts (see Table 2) was tested to optimize the solution. The mixing calculations for a sequence of lavas may be carried out in two different ways: (1) in incremental steps—e.g., "A"→"B"→"C" . . . , or (2) in cumulative (or successively larger) steps beginning with the same parent—e.g., "A"→"B", "A"→"C", etc. Both methods were used and found to yield essentially identical proportions of the various phases, however, the first method consistently gave smaller values for Σr_i^2 . In order to maintain consistency between different sets of calculations, the second method was arbitrarily used to evaluate the proportions of phenocryst

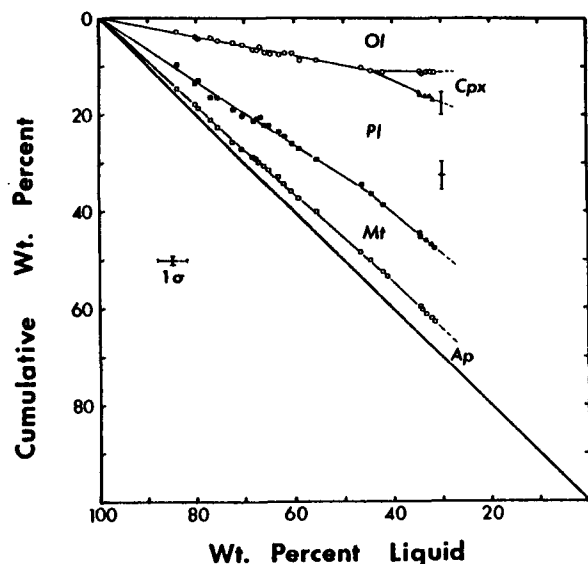


Fig. 4. Crystallization model for COM lavas as deduced from major-element mixing model calculations (see Table 7 and text). Uncertainties shown are those associated with the mixing calculations only.

phases and residual liquids ("B") throughout the COM suite. Representative cumulative and incremental fractionation models are summarized in Tables 7 and 8. Such calculations were carried out for all COM lavas and the proportions of fractionated phenocrysts were plotted against the fraction of liquid remaining (F) at the stage represented by each sample (Fig. 4). Differences between results of incremental and cumulative calculations consistently lie within the uncertainty limits shown in Figure 4.

The striking feature of this diagram is the implied fractionation of olivine, plagioclase, magnetite, and apatite in essentially constant proportions during the first 55 percent crystallization of initial liquid 69-22. Near that stage clinopyroxene entered as a liquidus phase at the expense of olivine, and the proportions of magnetite and apatite decreased noticeably, while that of plagioclase increased slightly. The entire range in composition of COM lavas corresponds to solidification of some 70 percent of a liquid similar to 69-22. If magma similar in composition to 69-28 was a more primitive predecessor of the COM suite, it is inferred that the observed lavas represent crystallization of about 80 percent of that liquid.

The empirically derived fractionation model closely resembles the phase relations inferred from the textural data and is by definition compatible with compositions of olivine and plagioclase phenocrysts in the natural rocks. These minerals display regular decreases in Fo and An content, respectively, as F decreases (Fig. 5). The model is also compatible with experimentally obtained

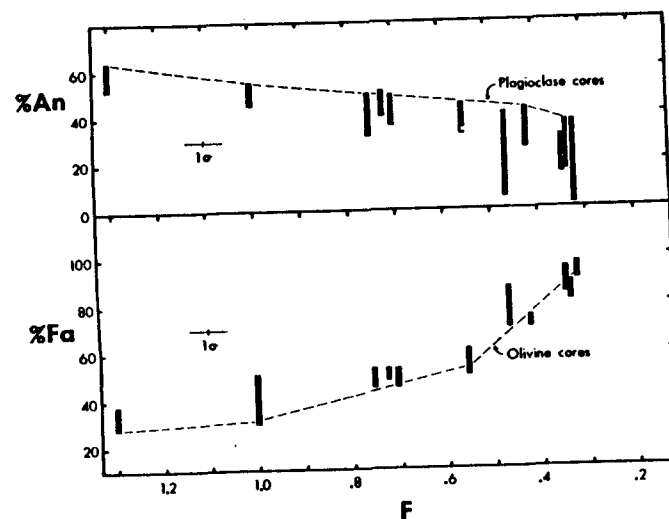


Fig. 5. Variation of mineral compositions in COM lavas as a function of degree of crystallization of respective samples (relative to sample 69-22). Dashed lines approximate the trend in composition of phenocryst cores. Solid bars indicate the range between phenocryst and groundmass compositions within each sample.

compositions and crystallization proportions of olivine and plagioclases. It should be noted that megacryst minerals occurring in the Lava Creek flow are not included in the fractionation models presented because (a) such megacrysts are not present in any other flow we examined, and they are rare even in the Lava Creek flow, and (b) major element trends as represented by normative compositions (see Fig. 3) are not consistent with significant clinopyroxene fractionation among the ferrobasalts. Model calculations involving the megacryst minerals did not yield significantly better mathematical solutions than those presented, and in any case the maximum amount of clinopyroxene that could be tolerated was less than two to three percent.

Also it was found that our model calculations for the ferrolatites were not significantly improved by including the partly-resorbed anorthoclase xenocrysts. At the most, no more than one to two percent of anorthoclase could be tolerated in obtaining a good mathematical solution. However, those models indicated that anorthoclase must be added to the melt rather than fractionated from it.

Trace Element Behavior during Crystallization of COM Magma

Treating the COM lava suite as a representative sampling of liquids formed by crystal fractionation of a single type of parental magma has yielded estimates of the fraction of liquid remaining at any stage in the differentiation of that magma. It is widely recognized that the concentrations of trace elements in such fractionated liquids are dependent upon (1) their concentrations in the initial magma, (2) the magnitude of the effective crystal/liquid partition coefficients (which are themselves functions of temperature, pressure, bulk composition, and, in some cases, oxygen fugacity), (3) the proportions of fractionated solid phases, and (4) the extent of fractionation.

The latter two factors were quantified for the COM suite in the previous section. The relative concentration of an element in a fractionated liquid may be expressed as $C_1/C_0 = F^{D-1}$ according to the Rayleigh fractionation model (c.f., [27]) which assumes that equilibrium is maintained only at crystal-liquid interfaces. C_0 and C_1 are respectively concentrations of the element in the initial liquid and the derived liquid, the proportion of which is F , and D is a composite bulk partition coefficient which is weighted according to proportions of the fractionated phases. In the case of elements which are usually excluded from early crystallizing phases (e.g., Rb, K, Th, Cs, Zr, Ba and the REE), the value of D approaches zero. Thus for a perfectly excluded element, $C_1/C_0 = F^{-1}$ (i.e., the inverse of the proportion of liquid remaining). This relationship also holds for excluded elements in the case of bulk (Nernst) equilibrium fractionation. Crystallization of such phases as zircon, apatite or micas may cause D to be greater than zero for some elements such as Zr, Hf, the REE, or Rb and K in which case these elements may no longer be perfectly fractionated into the residual liquid.

Data for selected excluded trace elements in COM lavas have been normalized to the concentrations in sample 69-22 and plotted against F in Figure 6A.

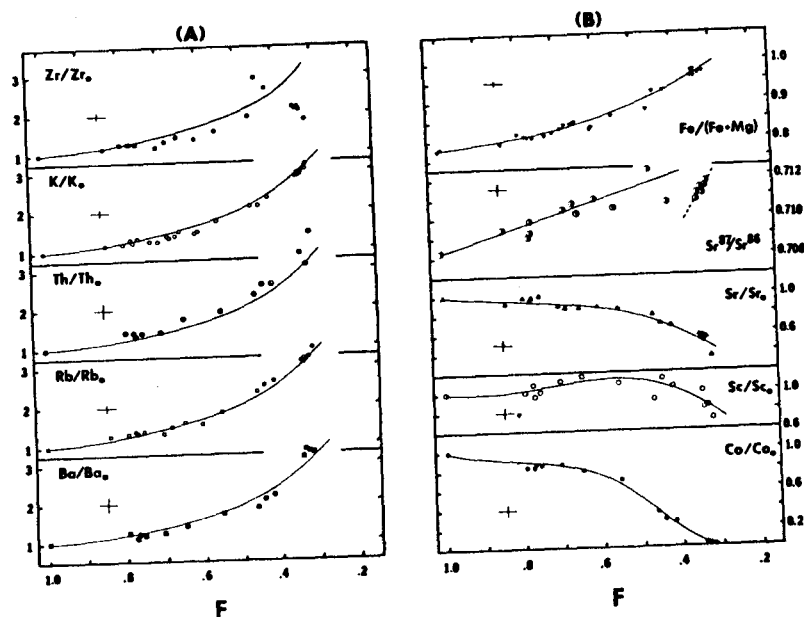


Fig. 6. (A) Relative concentrations (rock/69-22) of excluded elements as a function of degree of crystallization. Curves shown are those predicted for ideally excluded elements (see text). (B) Relative concentrations of selected included elements, $\text{Fe}/(\text{Fe} + \text{Mg})$, and $\text{Sr}^{87}/\text{Sr}^{86}$ as a function of degree of crystallization. Curves have no theoretical significance. In all cases estimated one-sigma uncertainties are indicated by a cross

For reference, a theoretical curve for perfectly excluded elements is shown in the plots for Ba, K, Rb, Th, and Zr. Note that each of these elements is more strongly enriched in residual liquids than in the bulk cumulate phases. One-sigma uncertainties are also shown for each element; these are based on combined analytical errors for both rocks used to calculate each data point and on uncertainties in the least-squares determination of F . Within the estimated uncertainties all of these elements follow the theoretical curves except for Zr (and Hf, not shown) which rises sharply in samples CM-2 and 69-19 ($F=0.45$) and subsequently decreases with decreasing F . The theoretical curves indicate the maximum possible concentration of an element during fractional crystallization of genetically related liquids, so in the case of these two samples an additional mechanism must be invoked. Since the other excluded elements in these samples are well-behaved it seems improbable that CM-2 and 69-19 are derived from a different parent magma having higher content of Zr and Hf. Rather, it is suggested that these samples either contain occult zircon or some other phase is unusually enriched in Zr and Hf. More evolved ferrolatites have apparently experienced zircon (?) fractionation. In spite of careful examination, zircon could not be seen in thin sections of these rocks, however, their fine grain

size would make the identification difficult. The excluded element data provide strong support for the basic postulate that all COM lavas are genetically related through fractional crystallization of magmas of common parentage.

Data for several included elements are displayed in the same fashion in Figure 6B. Sr and Co are steadily depleted throughout the sequence, whereas Sc is slightly enriched in the early stage liquids, then behaves as an included element after about 50 percent crystallization. The distinct breaks in the Co and Sc trends may be related to entry of clinopyroxene as a crystallizing phase. Other elements not shown follow predictable trends—e.g., Ni and Cr are substantially depleted by the time F reaches a value of 0.65. The REE behave as partially included elements owing to fractionation of apatite for which REE partition coefficients are high [28]. REE abundances in COM lavas, normalized to those in sample 69-22, increase with degree of crystallization, but with only slight enrichment of Sm, Eu and Tb compared to La and Lu. This type of fractionation results from removal of apatite, for which middle REE partition coefficients are greater than those for the lightest and heaviest REE (Leeman, in preparation).

Crustal Contamination

Major and trace element compositions of COM lavas are well-explained in terms of the crystal fractionation model presented here. Admixture of crustal material with COM magmas may have occurred to some extent, but cannot be called upon to explain the main variations in composition in these lavas (c.f., Fig. 1). Such features as extremely-high content of the elements Ba, Zr, Hf, Th, and U (in concentrations greater than those observed in most crustal rocks) and near-constancy of K/Ba and K/Rb ratios (both of which would tend to decrease with addition of average crustal material) argue against total assimilation of crustal rocks.

On the other hand, Sr and Pb isotopic ratios [14; Leeman and Manton, in preparation] vary systematically with chemical composition of COM lavas. In Figure 6B it is seen that $\text{Sr}^{87}/\text{Sr}^{86}$ ratios increase progressively with decreasing F . Also, the ferrolatites from the Devils Orchard, Serrate and Highway flows are heterogeneous and define a trend of increasing $\text{Sr}^{87}/\text{Sr}^{86}$ which is distinct from that of the ferrobasalts. These relationships are not expected to result from fractional crystallization as the two isotopes have the same chemical properties. The simplest explanation for these trends is that increases in $\text{Sr}^{87}/\text{Sr}^{86}$ reflect progressive crustal contamination of COM magmas as they differentiated in sub-surface reservoirs.

The available data suggest that if such contamination occurred, it must have been relatively selective with respect to Sr (and Pb) so as to preserve the major and other trace element characteristics of COM lavas. Alternatively, assimilation of small amounts of highly-radiogenic material is plausible. Lead isotopic analyses (Leeman and Manton, in preparation) show that some of the crustal xenoliths found in COM lavas are derived from terrains of Archean age. These xenoliths commonly contain abundant potash feldspar or plagioclase

and many contain (now-relict or partly resorbed) biotite. In rocks of Archean age alkali feldspars typically have high Pb/U and non-radiogenic lead [29], whereas biotites are characterized by high Rb/Sr and very radiogenic Sr [30]. It is conceivable that selective melting of small amounts of these minerals can account for the isotopic anomalies observed in COM lavas without greatly affecting their bulk compositions. It is concluded that the isotopic compositions of Pb and Sr in COM lavas have been perturbed by some form of crustal contamination which did not significantly affect the concentrations of most other elements in these rocks.

Origin of COM Lavas

The evidence presented here strongly suggests that COM lavas are related by fractional crystallization of a common parental magma-type, if not the same magma. Even the least-evolved samples are strongly fractionated in comparison to SRP olivine tholeiites, such as the McKinney Basalt [7, 11]. For reasons given earlier it is not likely that the high excluded element contents in COM lavas are the result of contamination. Two main possibilities remain: COM lavas may (1) indeed be derived by fractionation of SRP olivine tholeiite magma, or (2) be derived as separate partial melts that were not related directly to the SRP olivine tholeiites.

The first possibility was tested in terms of crystal fractionation models. Mixing calculations, such as those described earlier, fail to reveal a viable path from typical SRP olivine tholeiites to COM ferrobasalts by fractionation of low-pressure phenocrysts (olivine, plagioclase, spinel) observed in those rocks or by fractionation of phases (clinopyroxene, garnet) which crystallize from an olivine tholeiite at a pressure of 26 kbars [1]. A high-pressure path can be defined, though imprecisely, using compositions of minerals (olivine, clinopyroxene, plagioclase) formed in the 8 kbar experiments of Thompson [1]. According to this model, 22 percent of a parent tholeiite liquid similar to McKinney Basalt pillow lava must crystallize to obtain a liquid equivalent to 69-28; 41 percent must crystallize to obtain 69-22 liquid.

Abundances of excluded trace elements provide important constraints on the postulated fractionation of olivine tholeiite magma to yield COM ferrobasalts. Calculations were made to estimate the degree of fractionation required to account for observed contents of some excluded elements in ferrobasalt samples 69-28 and 69-22, assuming that these lavas were derived directly by fractionation of average McKinney Basalt magma [11]. As noted earlier, the relative concentration ($C_1/C_0 = \text{conc. in COM lava}/\text{conc. in McKinney avg.}$) for an excluded element is approximately equal to $1/F$, where F is the fraction of liquid remaining. Using observed trace element contents, values of F were calculated ($F = C_0/C_1$) for COM lavas 69-28 and 69-22. The elements Ba, Ta, Hf, Zr, and the REE yield reasonably concordant values of F which indicate approximately 55 percent (69-28) and 66 percent (69-22) crystallization of average McKinney magma to obtain the observed abundances of these elements in the ferrobasalts by the postulated model (see Table 9). These values are substan-

Table 9. Excluded trace element models for derivation of COM ferrobasalts by fractionation of McKinney basalt magma

	McK ^a avg.	"F" ^b 69-28	"F" ^b 69-22		McK ^a avg.	"F" ^b 69-28	"F" ^b 69-22
%K ₂ O	0.80	0.67	0.50	La	24.0	0.36	0.28
%P ₂ O ₅	0.55	0.26	0.22	Ce	54.0	0.38	0.30
Rb	16.6	0.69	0.55	Sm	7.6	0.44	0.34
Ta	1.7	0.42	0.28	Yb	3.4	0.52	0.41
Hf	5.8	0.50	0.36	Lu	0.56	0.50	0.41
Zr	278.0	0.44	0.32	Ba	380.0	0.54	0.39
Th	2.2	0.85	0.58				

^a Average values for McKinney Basalt [11, Table 7] used as hypothetical parent

^b "F" denotes the fraction of liquid remaining if the respective COM lavas were derived from "average McKinney Basalt" by perfect Rayleigh or Nernst fractionation, assuming that solid/liquid partition coefficients are essentially zero for each element; "F" = 1/C₁ = conc. in McK avg./conc. in COM lava. (1-F) = fraction of hypothetical parent that crystallized

tially greater than those inferred from the major element mixing calculations. It is also apparent that values of F in Table 9 are quite variable for other elements (e.g. K, Rb, P). These discrepancies likely indicate that the proposed model is not correct; i.e., average McKinney Basalt is not the parent of the COM ferrobasalts. Of course, this conclusion does not rule out the possibility that other olivine tholeiites (or their precursor liquids) could be parental to the COM lavas.

It is concluded that detailed refinement of the fractionation calculations must await more extensive experimental studies of SRP basalts. For the present, derivation of COM-type lavas from SRP olivine tholeiite magmas remains a viable possibility, particularly under conditions of moderate pressure (ca. 10 kbar) and water content [1, 24].

The second possibility, i.e., that COM-type lavas are derived as direct partial melts of the mantle, seems unlikely since COM lavas have: (1) high Sr⁸⁷/Sr⁸⁶ ratios in contrast to those of SRP olivine tholeiites; (2) relatively high iron enrichment (Fe/(Fe + Mg) ranges from 0.7 to 0.8 in the most mafic COM lavas); (3) REE abundance patterns which display strong enrichment of light REE relative to heavy REE and overall enrichment in REE relative to SRP olivine tholeiites, and (4) strong enrichment in excluded elements and depletion of included elements such as Cr, Ni, and Co. This combined evidence is more compatible with an origin of these lavas by fractionation of some precursor magma(s) than by direct melting of the mantle.

Conclusions

Mineralogic, petrographic, and geochemical evidence suggests that COM lavas are members of a genetically related suite of liquids that were derived from a common parental magma (or magma-type). These lavas evolved in composition

by cotectic crystallization of olivine, plagioclase, magnetite, and apatite in the mafic members of the suite (ferrobasalts), and by cotectic crystallization of plagioclase, magnetite, clinopyroxene, and minor olivine in the silicic members (ferrolatites). Phenocrysts of olivine became more Fe-rich, and those of plagioclase became more sodic as crystallization proceeded. Assuming that COM lavas are related by crystal fractionation, the observed range in composition requires at least 70 percent crystallization of the most primitive ferrobasalt liquid.

Acknowledgements. We wish to express our thanks to Daniel F. Weill of the University of Oregon for permission to use the electron microprobe and experimental facilities, to Professor Gordon G. Golez also of the University of Oregon for use of the neutron activation facilities, to W.I. Manton of the University of Texas at Dallas for use of the mass spectrometer and laboratory facilities there, and finally, to M.E. Coller, Chemist in the Silicate Chemical Laboratory of the Geology Department at Indiana University, for the wet silicate analyses. W.P. Leeman acknowledges financial support from the National Science Foundation (Graduate Fellowship), the Geological Society of America Penrose Fund, the National Geographic Society, and the University of Oregon Geology Department Student Research Fund.

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