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The isotopic composition of strontium has been measured in 54 basalts and associated igneous rocks from the Snake River Plain, southern Idaho. Thirty Pliocene-Holocene olivine tholeiites have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.7060 to 0.7080 and averaging 0.7070 ± 0.0003 (2σ); 17 basalts and associated latites from Craters of the Moon, King Hill, and the Blackfoot River Canyon have ratios ranging from 0.7080 to 0.7180. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the tholeiites are similar to those in other continental tholeiites, but are greater than those in oceanic basalts and in alkali-olivine basalts from the Basin-Range province. The constancy in isotopic composition suggests that the high ratios are characteristic of the parent magma(s) and are not due to crustal contamination. Major and trace element data suggest that the Craters of the Moon lavas are differentiates of the olivine tholeiites. The high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of these lavas may be explained by crustal contamination of small volumes of tholeiitic magma which differentiated at shallow depth in a Precambrian metamorphic terrain near the margins of the Snake River Plain. Pliocene silicic volcanic rocks which may underlie the Snake River basalts are not a likely source of contamination, because five such rocks have present-day $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.7110 to 0.7134.

1. Introduction

Measurements of the isotopic composition of strontium have been widely applied in petrogenetic studies of basaltic rocks. The narrow range of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios observed in most oceanic basalts (0.7025–0.704) is generally accepted as representative of the oceanic mantle composition, although some studies indicate that lateral or vertical variations in mantle isotopic composition may exist (e.g. Gast et al. [1]). $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in continental basalts are observed to be more variable and somewhat higher (0.703–0.712) than in

oceanic basalts. Owing to the enrichment of Rb in the crust and, therefore, ^{87}Sr in old crustal rocks (Hurley [2]), the higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in continental basalts have often been attributed to contamination by crustal rocks. The means by which such contamination may occur are not at all clear; bulk assimilation of crustal rocks (Faure and Hurley [3]), selective contamination (Heier et al. [4]; Green and Ringwood [5]), diffusion of radiogenic strontium (Heier [6]), and isotopic exchange with country rocks (Pankhurst [10]) have been suggested. Lateral variations in isotopic composition of basaltic lavas have been attributed to lateral inhomogeneity of source regions in the mantle or variations in the depth of melting (Hedge [7]; Leeman [9]).

A number of continental tholeiitic suites are of

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Table 1
Strontium isotopic composition and age of continental tholeiitic effusive and intrusive rocks.

Location and description	Age (my)	$^{87}\text{Sr}/^{86}\text{Sr}_0$ a)	Reference
Cenozoic			
Snake River Plain, olivine basalts COM-type basalts, latites	0-10	0.7070 ± 0.0003 b) $0.7080 - 0.7180$	this paper, [7] this paper, [14]
Columbia River Plateau, olivine basalts	13-25	0.7055 ± 0.0007	[42] c)
Yellowstone Park and vicinity, basalts	10-30	0.7061 ± 0.0008 $0.7061 - 0.7085$	[3], [34] [45] c)
Skye, Scotland, gabbros ferrodiorites	55	0.7058 ± 0.0010 0.7123 ± 0.0008	[46]
Skaergaard Intrusion, lower gabbros upper border group	50	0.7065 ± 0.0010 0.7092 ± 0.0027	[11]
Mesozoic			
Deccan, India, basalts	100	0.7063 ± 0.0005	[3]
Serra Geral, Brazil, basalts, dolerites	120-147	0.7060 ± 0.0003	[12]
Antarctica, Ferrar Group dolerites Queen Maude land dolerites	150	$0.7090 - 0.7143$ 0.7055 ± 0.0006	[12], [13] [13]
Tasmania, dolerites	165	0.7118 ± 0.0005	[4]
Karoo, Southern Africa, dolerites, basalts	154-190	0.7060 ± 0.0008	[12]
Newark Series, Palisades diabase Brookville diabase	190	0.7055 ± 0.0020 0.7058	[3] [47] c)
Southern Africa, Lebombo basalts Nuanetsi basalts, gabbros	205	$0.7046 - 0.7066$ $0.7063 - 0.7130$	[8]
Paleozoic			
Garabal Hill-Glenn Fyne, Scotland, gabbros	392 ± 17	0.7052 ± 0.0020	[48]
Insch, Scotland, gabbroic rocks upper differentiates	510 ± 13	$0.7032 - 0.7117$ 0.7123 ± 0.0001	[10]
Precambrian			
Endion Sill, Minnesota, gabbroic rocks	1092 ± 15	0.7046 ± 0.0006	[50]
Duluth, Minnesota, gabbroic rocks	1115 ± 14	0.7055 ± 0.0003	[50]
Trompsburg, Africa, gabbroic rocks	1372 ± 142	0.7043 ± 0.0004	[49]
Losberg, gabbros, norites	1881 ± 282	0.7064 ± 0.0024	[49]
Bushveld Complex, norites, anorthosites	1954 ± 30	0.7065 ± 0.0020	[49]
Great Dyke, gabbroic rocks	2541 ± 30	0.7024 ± 0.0008	[49]
Stillwater Complex, gabbroic rocks	2600 ± 300	0.7020 ± 0.0010	[51]
Modipe, gabbros	2630 ± 470	0.7010 ± 0.0010	[52] c)
Superior Province, metabasalts, greenstones	2700	0.7021 ± 0.0004	[53]
Usushwana, gabbroic rocks	2874 ± 300	0.7031 ± 0.0028	[49]

a) Initial ratio adjusted to $^{87}\text{Sr}/^{86}\text{Sr} = 0.7084$ in Fimer and Amend Standard.

b) Error is 2σ (95%) confidence limit or error in isochron calculation, if reported.

c) No data given for strontium standard, published value used.

particular interest because they are characterized by unusually high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and, in some cases, by progressive increase in this ratio during differentiation. $^{87}\text{Sr}/^{86}\text{Sr}$ in rocks from the marginal border group through the upper border group of the Skaergaard intrusion increases from 0.706 to 0.710 (Hamilton [11]), and similar variations are reported for gabbroic differentiates at Inch, Scotland (Pankhurst [10]). Some of the highest ratios reported for basaltic rocks (0.712) occur in dolerites from Tasmania (Heier et al. [4]) and Antarctica (Compston et al. [12]; Faure et al. [13]). A compilation of published isotopic data for continental tholeiitic rocks is presented in table 1.

Hedge and Walthall [14] and Hedge [7] published six analyses of basalts from the Snake River Plain, Idaho, that showed $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.706 to 0.712; the highest ratios were observed in Holocene lavas from Craters of the Moon National Monument. We undertook a detailed investigation of the Snake River basalts to examine the nature of isotopic variations in these tholeiitic lavas. This area was chosen for study because a large amount of petrologic, geophysical, and stratigraphic data are available for the region, thus providing numerous constraints for interpretation of the isotopic data.

2. Geologic setting

The Snake River Plain is a broad topographic depression which extends for 500 km across southern Idaho (fig. 1). This depression contains a great thickness (locally greater than 1 km) of basaltic lavas and interbedded continental sediments. The western portion of the plain is bounded by northwest trending normal faults (Malde [16]), whereas apparently the eastern portion is not fault-bounded but is predominantly downwarped. The central plain is cut by a north to northwest trending fissure zone (Idaho Rift Zone) that extends almost 100 km from Craters of the Moon National Monument on the north to the Wapi lava field on the south (Prinz [17]). Rocks exposed north and south of the Snake River Plain include Pliocene and Miocene silicic and intermediate lavas and tuffs, Mesozoic intrusive rocks of the Idaho batholith and associated bodies, and Paleozoic sedimentary rocks. Precambrian metamorphic rocks (2.46 by) are exposed in the Albion Range, southern Idaho (Armstrong

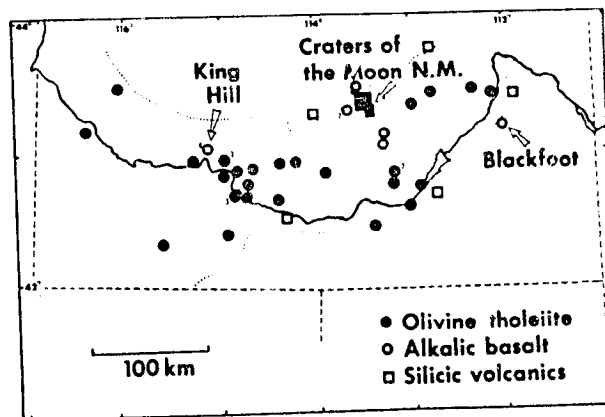


Fig. 1. Map of Snake River Plain (within dotted lines) indicating sample locations. Small numbers beside locations indicate the number of samples represented. Detailed locations in the Craters of the Moon area are given in fig. 2. (COM-type lavas are denoted as alkalic basalt.)

and Hills [18]). Stratigraphic control is good in the western Snake River Plain where Malde and Powers [19] have subdivided the post-Miocene rocks into three units: (a) lower and middle Pliocene Idavada Volcanics, (b) upper Pliocene to middle Pleistocene Idaho Group, and (c) upper Pleistocene to Holocene Snake River Group. The Idavada Volcanics consist mainly of silicic volcanic rocks whereas the Idaho and Snake River groups consist of interbedded basaltic lavas and continental sediments. Most of the samples examined in the present study belong to the latter two units or their equivalents in the eastern plain. Other aspects of late Cenozoic geology of the Snake River Plain are described by Stearns et al. [20], Carr and Trimble [21], and Malde [22].

3. Geophysical investigations

Gravity studies [23–25] reveal large positive en echelon Bouguer anomalies in the western Snake River Plain. Seismic refraction studies [26] in the same area indicate an anomalous crustal structure beneath the western Plain with a thin (8–10 km) 5.2 km/sec layer underlain by a thick (33–38 km) 6.7 km/sec layer. Low P_n velocities (7.9 km/sec) in the underlying mantle suggest that this region is highly absorptive or that a low-velocity layer lies immediately beneath the

Mohorovičić discontinuity. The gravity and seismic studies suggest that mafic material intrudes to a depth of 8–10 km beneath the western Plain and is overlain by a layer of rocks having V_p similar to that in interbedded basaltic lavas and sediments on the island of Hawaii.

Gravity studies in the eastern Snake River Plain [24,27] reveal low-relief, northwest-southeast trending linear anomalies. Lafehr and Pakiser [24] suggest that less basalt accumulated in this region than in the western Plain, and that the basalt filled troughs or valleys in an undulating subsurface basement. Overall the geophysical data suggest that the western Plain is underlain by predominantly simatic crust whereas the eastern Plain is underlain by a more sialic crust.

4. Petrochemistry

The Snake River basalts are dominantly olivine tholeiites that are characterized by a high degree of mineralogical and chemical similarity (Stone [28,29]; Leeman, in preparation). Subordinate volumes of alkali- and iron-enriched basalts and associated latitic lavas having tholeiitic affinities occur at widely separated locations in the Snake River Plain at Craters of the Moon National Monument, near King Hill, and near Blackfoot [30–33]. These lavas are hereafter denoted as COM-type lavas. The olivine tholeiites are composed of olivine ($Fe_{80}-Fe_{50}$), labradorite, augite, and opaque minerals (iron-titanium oxides) with variable amounts of glass; deuteric alteration products

Table 2
Average compositions and molecular norms of Snake River Plain volcanic rocks.

	Olivine tholeiites (78) ^a	COM-type basalts (28)	Latites (10)	Idavada Volcanics (4)
SiO ₂	46.90	49.28	62.09	74.55
TiO ₂	2.69	2.98	0.82	0.39
Al ₂ O ₃	15.06	13.79	14.27	12.80
Fe ₂ O ₃	3.05	2.28	2.40	1.63
FeO	10.72	12.93	7.61	0.82
MnO	0.20	0.27	0.20	0.04
MgO	7.63	3.76	0.52	0.22
CaO	10.03	7.27	3.42	1.03
Na ₂ O	2.53	3.36	3.99	3.06
K ₂ O	0.61	2.23	4.38	5.42
P ₂ O ₅	0.58	1.83	0.29	0.05
Or	3.66	13.57	26.39	32.56
Ab	23.05	31.07	36.54	27.93
An	28.36	16.45	8.26	4.86
Q	—	—	10.69	31.62
Di	14.63	6.69	5.69	—
H _y	12.30	18.69	8.09	0.68
Ol	9.73	2.86	—	—
Mt	3.24	2.45	2.56	1.11
Il	3.80	4.28	1.16	0.55
Ap	1.23	3.95	0.62	0.11
Norm Plag.				
%An	55.16	34.61	18.44	14.83

a) Number of samples used to calculate averages is given in parentheses.

Data from Stone [29, personal communication], Stone et al. [31], H.E. Malde (personal communication), and Leeman (unpublished data).

(mainly montmorillonite) occur in some of the older basalts. The COM-type basalts contain iron-rich olivine, sodic andesine, abundant magnetite, and apatite, usually enclosed in a matrix of opaque glass containing crystallites of these same minerals plus augite. The latites are composed of microlites of augite, alkali feldspar or sodic plagioclase, and magnetite in a glassy matrix; some contain partially absorbed xenocrysts of sanidine or anorthoclase. Some samples from King Hill and Craters of the Moon contain minor xenocrysts of alkali feldspar or andesine. Several flows from Craters of the Moon contain xenoliths of granitic and gneissic rocks.

Average chemical analyses and norms of Snake River Plain olivine tholeiites, COM-type basalts and latites, and Pliocene silicic volcanic rocks are given in table 2. Differentiation trends for the basaltic lavas indicate iron-enrichment approaching that in some Skaergaard and Duluth differentiates [34,35]. Available field, mineralogical, and chemical data suggest that Craters of the Moon lavas are genetically related to the Snake River olivine tholeiites dominantly by processes of fractional crystallization [31].

5. Analytical details

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios were measured on a 12-inch Nier-type mass spectrometer. Descriptions of this instrument and the analytical techniques may be found in refs. [8] and [9]. The precision of a $^{87}\text{Sr}/^{86}\text{Sr}$ measurement is estimated to be 0.0002 on the basis of pooled replicate analyses that have been carried out in this laboratory over a number of years. Since the internal standard deviation of a single run (10–15 sets of ratio measurements) also averages about 0.0002, the variation between replicate analyses may be attributed solely to instrumental error; contributions of contamination and sample inhomogeneity to the variance are considered negligible. In view of this finding, we felt justified in not analyzing all our samples in duplicate; however, duplicate analyses were made on all samples critical to our arguments. The Eimer and Amend SrCO_3 standard was measured to have an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7084 ± 0.0002 (5 analyses, 95% confidence level).

Rb and Sr abundances were measured by atomic absorption using a Perkin-Elmer 303 spectrometer. Replicate analyses were generally reproducible within

5 percent for Rb and within 10 percent for Sr. Good agreement was obtained between our analyses of W-1 (Rb = 21 ppm, Sr = 191 ppm) and BCR-1 (Rb = 48 ppm, Sr = 348 ppm) and recommended values for these standard rocks. Five samples were analyzed for Rb and Sr by isotope dilution techniques [36].

6. Results

Sample locations, Rb and Sr abundances, and isotopic compositions are presented in table 3. Sample locations are also indicated in figs. 1 and 2. Table 3 includes the analyses by Hedge and Walthall [14] and Hedge [7] for comparison; these analyses are adjusted to a value of 0.7084 for the Eimer and Amend standard. The samples are ordered stratigraphically according to the section of Malde and Powers [19]. Histograms of the isotopic compositions are given in fig. 3.

The olivine tholeiites are fairly uniform in isotopic composition (0.7060–0.7080), averaging 0.7070. There is more scatter in the data for the older basalts; which may be related to secondary alteration effects in several of these samples. Within-flow variations in isotopic composition are within analytical uncertainty with the exception of the Clover Creek basalts which contain variable amounts of saponitic alteration material. Rb contents and Rb/Sr ratios appear to increase with decreasing age of the basalts; some variations in this trend may be attributed to uncertainty in determination of concentrations as well as effects of secondary alteration in the older basalts.

The COM-type lavas have systematically higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than the olivine tholeiites. Craters of the Moon samples are uniformly high (0.7090–0.7108); those analyzed by Hedge and Walthall have higher ratios (0.7111, 0.7119), and two samples (69–22 and 69–28) have lower ratios (0.708). Two gneiss xenoliths from the Monument have ratios of 0.7177 and 0.7275.

The Pleistocene King Hill lavas have higher and more variable $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and lower Rb contents and Rb/Sr ratios than the Craters of the Moon basalts. The isotopic compositions range from 0.7107 to 0.7142 in the King Hill basalts and 0.7180 in a latite. A basalt from the Blackfoot River canyon near the southeastern margin of the Snake River Plain is isotopically and chemically similar to some Craters of the Moon basalts.

Table 3
Rb and Sr concentrations (ppm) and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of rocks from the Snake River Plain.

Age	Sample	Description	Location		Rb	Sr	⁸⁷ Rb/ ⁸⁶ Sr a)	⁸⁷ Sr/ ⁸⁶ Sr b)
			N. Latitude	W. Longitude				
Olivine tholeiites								
Recent	69-G	Crystal Ice Caves flow (2130 yr old)	42°57'	113°14'	5	230	0.06	0.7060 d)
	P-1	Wapi lava field, near Pillar Butte	42°53'	113°13'	9	207	0.13	0.7067
	P-5	King's Bowl, ejecta block	42°57'	113°14'	11	296	0.11	0.7069
	SBR-3 c)	Hells Half Acre, lava field	43°33'	112°26'	15	321	0.14	0.7069 d)
	SBR-6 c)	Basalt near Richfield	43°08'	114°04'	16	351	0.13	0.7070 d)
	D-1655	Dietrich basalt	42°53'	113°53'	14	303	0.13	0.7073
	Hedge	Dietrich basalt	—	—	10.2	268	0.11	0.7079 e)
	WPL-84	Shoshone basalt	42°59'	114°24'	14	275	0.15	0.7073
	Hedge	Shoshone basalt	—	—	16.2	281	0.17	0.7081 e)
Upper Pleistocene — Recent	B-418	McKinney basalt	43°01'	114°52'	13	292	0.13	0.7068
	D-1649	Wendell Grade, basalt	42°48'	114°45'	10	261	0.11	0.7072
	Hedge	Wendell Grade, basalt	—	—	12.8	235	0.16	0.7070 e)
	D-1652	Sand Springs, basalt	42°43'	114°50'	12	264	0.13	0.7070
	WPL-83	Sand Springs, basalt	42°39'	114°26'	12	289	0.12	0.7068
	D-1648	Thousand Springs basalt	42°40'	114°47'	13	321	0.12	0.7070
	WPL-82	Malad member, Thousand Springs basalt	42°54'	114°43'	15	255	0.17	0.7067
	WPL-88	Nuclear Reactor Test Site basalt	43°31'	112°50'	11	315	0.10	0.7068
	SBR-2 c)	Basalt near Idaho Falls	43°29'	112°13'	12	284	0.12	0.7060 d)

Table 3 (continued)

Age	Sample	Description	Location		Rb	Sr	⁸⁷ Rb/ ⁸⁶ Sr a)	⁸⁷ Sr/ ⁸⁶ Sr b)
			N. Latitude	W. Longitude				
Olivine tholeiites								
Lower Pleistocene	D-1687	Hammett basalt	42° 57'	115° 23'	9.1	319	0.08	0.7079
	WPL-102	Bruncau basalt, near Boise	43° 24'	116° 01'	8.0	300	0.08	0.7071
	WPL-103	Basalt, near Idahome	42° 32'	113° 28'	8.6	221	0.11	0.7070
	P-81	Big Southern Butte, north slope	43° 25'	113° 01'	11	252	0.13	0.7068
	69-17	Flow on east side of COM lava field, 3 mi. west of Cox's Well	43° 11'	113° 18'	64	300	0.61	0.7104
	69-19	Devil's Orchard flow (crystalline latite)	43° 28'	113° 32'	82	230	1.02	0.7107 d)
	69-20	Devil's Orchard flow (glassy latite)	43° 28'	113° 32'	94	190	1.43	0.7108
	69-22	Lava Creek flow	43° 31'	113° 34'	35	360	0.28	0.7081 d)
	69-28	Great Rift eruption (< 2080 yr. old) on east side COM lava field	43° 15'	113° 18'	29	300	0.28	0.7079 d)
	69-35	Ejecta block, Yellow-jacket waterhole	43° 24'	113° 30'	77	300	0.74	0.7127
	Hedge	Indian Tunnel basalt	43° 27'	113° 24'				0.7111 e)
	Hedge	Highway "ande- site" (latite)	43° 28'	113° 34'				0.7119 e)
	SI-1	Gneiss xenolith, Serrate flow	43° 28'	113° 31'	10	75	0.38	0.7177
	CK-1	Gneiss xenolith, Carey Kipuka	43° 20'	113° 38'	40	155	0.74	0.7275
Pleistocene (?)	P-87	Basalt along Blackfoot River, near Alridge	43° 15'	112° 02'	45	331	0.39	0.7093

Table 3 (continued)

Age	Sample	Description	Location		Rb	Sr	⁸⁷ Rb/ ⁸⁶ Sr a)	⁸⁷ Sr/ ⁸⁶ Sr b)
			N. Latitude	W. Longitude				
Olivine tholeiites								
Upper Pliocene—Pleistocene	D-1681	Upper flow, King Hill basalt, Bruneau Fm.	43°01'	115°17'	23.5	488	0.14	0.7107 d)
	69–60	Upper flow, King Hill basalt, Bruneau Fm.	43°03'	115°13'	56	420	0.38	0.7136 d)
	69–61	Upper flow, King Hill basalt, Bruneau Fm.	43°03'	115°13'	36	515	0.20	0.7114 d)
	D-1682	Lower flow, King Hill basalt, Bruneau Fm.	43°03'	115°14'	27	355	0.22	0.7142
	69–62	Lower flow, King Hill basalt, Bruneau Fm.	43°03'	115°13'	42	400	0.30	0.7126 d)
	D-1683	Middle flow (latite), King Hill basalt, Bruneau Fm.	43°03'	115°13'	61	277	0.64	0.7180
Upper Pliocene	D-1684	Clover Creek basalt, Glenns Ferry Fm.	43°01'	114°59'	9.4	230	0.12	0.7068
	D-1685	Clover Creek basalt, Glenns Ferry Fm.	42°59'	115°02'	8.2	256	0.09	0.7076 d)
	D-1686	Clover Creek basalt, Glenns Ferry Fm.	42°59'	115°01'	6.9	248	0.08	0.7080 d)
	Hedge	Clover Creek basalt, Glenns Ferry Fm.	—	—	11.5	247	0.13	0.7064 e)
	E-2247	Little Creek basalt, American Falls Dam	42°46'	112°53'	5.6	281	0.06	0.7070 d)
	P-6	Massacre Rocks, basaltic plug	42°40'	113°00'	8.2	214	0.11	0.7071

Table 3 (continued)

Age	Sample	Description	Location		Rb	Sr	⁸⁷ Rb/ ⁸⁶ Sr a)	⁸⁷ Sr/ ⁸⁶ Sr b)
			N. Latitude	W. Longitude				
Olivine tholeiites								
Middle Pliocene	D-1654	Upper Banbury basalt	42°43'	114°51'	8.2	325	0.07	0.7070
	D-1653	Lower Banbury basalt	42°44'	114°51'	6.7	285	0.07	0.7072
	A-196	Lower Banbury basalt	42°54'	115°00'	6.4	310	0.06	0.7074 d)
	WPL-80	Banbury basalt, near Murphy	43°10'	116°30'	7.7	210	0.11	0.7060 d)
	P-37	Banbury basalt, near Roseworth	42°25'	114°58'	5.8	205	0.08	0.7074 d)
Idavada Volcanics (Lower Pliocene)	I-4120	Idavada basalt	42°20'	115°39'	6.2	170	0.11	0.7068 d)
COM-type basalts and latites								
Snake River Group (Recent)	Craters of the Moon Lava field							
	WPL-86	Flow along US 20-26, 5 mi. south of Fish Lake Reservoir	43°22'	113°45'	42	336	0.36	0.7092
	WPL-87	Flow along US 20-26, 5 mi. south of Fish Lake Reservoir	43°22'	113°45'	41	326	0.36	0.7090
	SBR-4 c)	Sunset Crater basalt	43°29'	113°32'	42	319	0.38	0.7098 d)
	SBR-5 c)	Big Craters N.W. basalt	43°26'	113°36'	50	296	0.49	0.7101 d)
Silicic volcanic rocks								
Pliocene	F-2248	Vitrophyre, near American Falls	42°47'	112°49'	170	75	6.5	0.7134 d) 0.7129 f)
	F-2250	Obsidian tuff, near Ammon	43°30'	111°56'	164	32	14.8	0.7121 0.7110 f)
	F-2251	Obsidian pellets, near Howe	43°48'	112°50'	190	37	14.7	0.7127 d) 0.7117 f)
	F-2252	Pumice scoria, near Carey	43°18'	114°01'	167	59	8.1	0.7125 0.7119 f)
	69-45	Vitrophyre, Shoshone Falls "andesite"	42°35'	114°22'	128	90	4.0	0.7110 0.7107 f)

a) Atom ratio.

b) Normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$.

c) Rb and Sr determined by isotope dilution.

d) Average of two replicate analyses.

e) Analysis taken from literature. $^{87}\text{Sr}/^{86}\text{Sr}$ adjusted to $^{87}\text{Sr}/^{86}\text{Sr} = 0.7084$ in Finner and Amend SrCO_3 standard.

f) Initial ratio, calculated assuming age of 5 my.

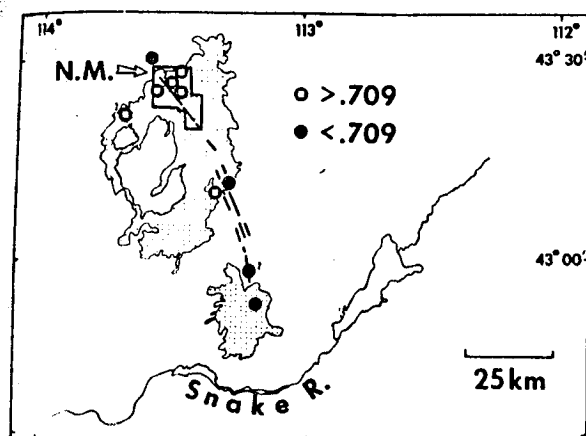


Fig. 2. Map of recent lava fields along the Idaho Rift Zone (heavy broken lines). N.M. is Craters of the Moon National Monument. Stippled areas represent recent lava fields. This diagram indicates the variability in isotopic composition of lavas extruded along the rift zone. Xenolith locations (see table 4b) are not shown. Small numbers beside locations indicate the number of samples represented.

Several Pliocene silicic volcanic rocks from margins of the Snake River Plain have present-day $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.7110 to 0.7134. Owing to their high Rb/Sr ratios, corrections for the generation of radiogenic Sr have been applied assuming an age of 5 my; the initial ratios range from 0.7107 to 0.7129.

7. Discussion

7.1. Olivine tholeiites

High titanium and low silica and alkali contents of the Snake-River olivine tholeiites appear consistent with a mantle origin for these lavas. Their limited range in major oxide composition (Stone [29]; Tilley and Thompson [37]) suggests that the parent magma(s) underwent little fractional crystallization or contamination en route to the surface [38]. On the other hand composition trends of sensitive trace elements in these lavas (e.g. apparent increasing Rb concentration with time) seem to require at least limited differentiation. Although the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in these basalts are moderately high, the uniformity of this ratio in basalts having a wide spatial and temporal distribution suggests that it is characteristic of the parent magma(s). As with

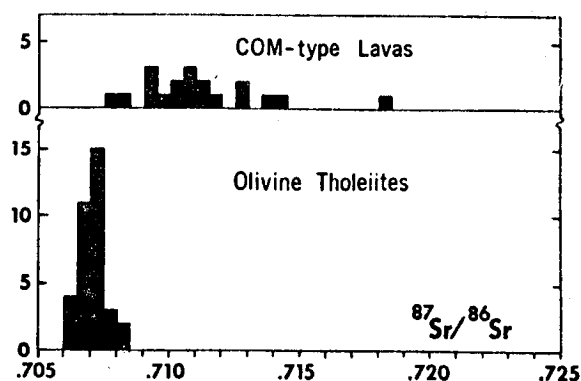


Fig. 3. Histogram of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in basalts from the Snake River Plain.

other continental tholeiites, several hypotheses can be offered to explain the Sr-isotopic composition of the Snake River basalts. It seems likely that these basalts either were derived from a mantle region characterized by a fairly constant Rb/Sr ratio higher than that in the source regions of most oceanic basalts, or were contaminated in some way by crustal Sr.

We have considered the various contamination mechanisms listed earlier, and conclude that bulk contamination by crustal materials exposed at the surface cannot account for the high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios observed in the Snake River tholeiites and simultaneously preserve their basaltic bulk chemistry, considering the large amounts of contaminant generally required. It is possible that selective ^{87}Sr -contamination has occurred in such a way that the effect on bulk composition is not readily detectable. The greatest difficulty with such hypotheses is that contamination must have occurred efficiently on a tremendous scale to have produced large volumes of isotopically homogeneous lavas over a wide area and long time span. Similar arguments against contamination can be made for other continental tholeiite provinces, but in most cases there are insufficient data to fully evaluate these arguments. In the Snake River Plain, however, geophysical evidence supports conclusions based on geochemical data. The western Plain is apparently underlain by thick simatic crust with little sialic material present. In this region, at least, there seems to be little opportunity for crustal contamination, except perhaps near margins of the graben where upfaulted sialic basement is exposed.

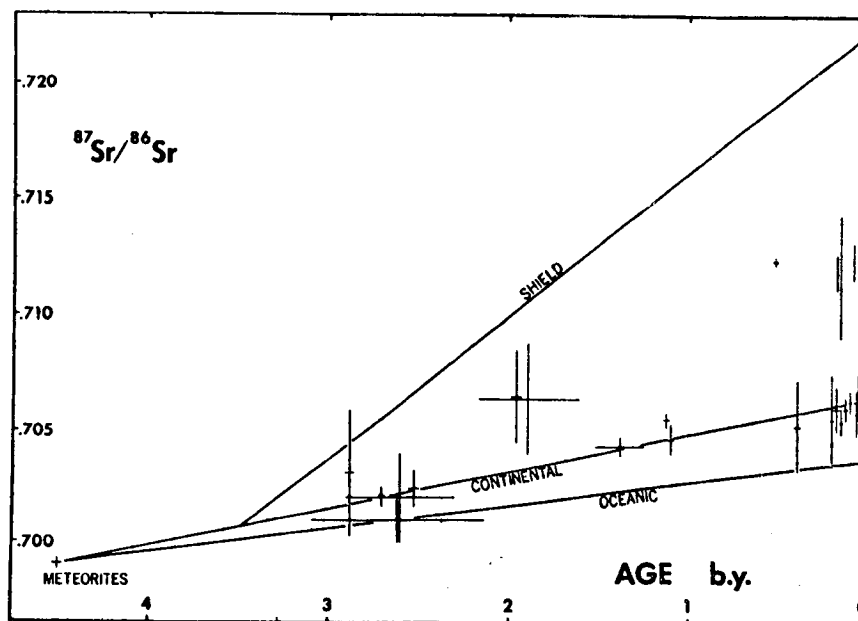


Fig. 4. Single-stage $^{87}\text{Sr}/^{86}\text{Sr}$ evolution diagram based on oceanic basalts ($\text{Rb}/\text{Sr} = 0.025$) and continental tholeiites ($\text{Rb}/\text{Sr} = 0.04$); evolution of Precambrian shield (Rb/Sr estimated as 0.15), assuming crust-mantle segregation 3500 my ago, is shown for reference. The oceanic regression is based only on data for oceanic basalts (average $^{87}\text{Sr}/^{86}\text{Sr} \approx 0.7035$; see [9] for refs.); continental regression is based on data in table 1, except for Snake River COM-type basalts, Skaergaard Upper Border Group, Lebombo-Nuanetsi basalts, and Insch gabbroic rocks, all of which display wide variation in initial $^{87}\text{Sr}/^{86}\text{Sr}$ so that no meaningful average could be calculated. To preserve clarity, the data points are not identified. Data which fall above the continental regression include Bushveld and Losberg intrusions, Tasmanian and Antarctic dolerites, and upper differentiates from Insch and Skye; only the Modipe gabbro, for which no standard analysis was quoted, falls close to the oceanic regression.

The other possibility we consider is that the Snake River olivine tholeiites were derived from a relatively homogeneous mantle source having high $^{87}\text{Sr}/^{86}\text{Sr}$. The isotopic homogeneity of these basalts and the arguments against contamination support this alternative. If the observed $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are representative of the source region of the Snake River basalts, then significant compositional differences exist between mantle underlying the Snake River Plain and most sub-oceanic mantle regions (excluding some oceanic islands). For example, most oceanic basalts (particularly ocean-ridge types with very low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios) are apparently derived from material that has been depleted in Rb for a considerable time compared to the source material for the Snake River basalts. Such variations in mantle isotopic composition could arise from vertical differentiation, lateral variation in composition (i.e., Rb/Sr), or differences in the time during which portions of the mantle have behaved as closed

systems with respect to Rb and Sr.

Strontium isotopic data for other continental tholeiites (see table 1) are compared in fig. 4, a $^{87}\text{Sr}/^{86}\text{Sr}$ -evolution diagram, to remove the influence of age differences. In this diagram primordial Sr is represented by that in achondritic meteorites and the age of the Earth is taken as 4.55 by. It is significant that all of the continental tholeiite data lie above a growth-line defined by average modern-oceanic basalt ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7037$, $\text{Rb}/\text{Sr} = 0.025$). Furthermore, most of the continental tholeiite data fit a growth-line corresponding to a Rb/Sr ratio of about 0.04. This line is an estimated best-fit and may vary somewhat considering the experimental errors; however, it provides an estimate of the minimum time-integrated Rb/Sr ratio in many sub-continental mantle regions. A similar Rb/Sr ratio has been inferred for "least depleted" sub-oceanic mantle based on data for alkalic lavas from some oceanic islands [39]. It is appreciated

that some of the continental tholeiite data may represent averages that are not representative of the mantle, but without more complete data effects of contamination and mantle inhomogeneity cannot be reliably evaluated. A number of tholeiites lie above the estimated continental tholeiite growth-line, but in cases where sufficient data exist these appear to be highly evolved (Insch and Skye ferrogabbros) or chemically unique (Tasmanian and Antarctic [Farrar] dolerites). Presumably these originate by shallow differentiation where crustal contamination possibly occurred, or they are derived from unique (mantle) source regions characterized by high $^{87}\text{Sr}/^{86}\text{Sr}$.

7.2. COM-type basalts

The high and variable $^{87}\text{Sr}/^{86}\text{Sr}$ ratios observed in Snake River COM-type basalts and associated latites suggest that these lavas are not primitive mantle-derived lavas. However, the presence of such lavas at widely separated locations suggests that they are produced by recurring localized conditions. Chemically and mineralogically these lavas appear to be differentiates of olivine tholeiite magma; most are quartz-normative implying that they underwent shallow fractionation [31,37].

The isotopic compositions of Craters of the Moon and Blackfoot River basalts may be explained by varying degrees of isotopic equilibration with shallow crustal rocks near the margins of the Snake River Plain. Fig. 2 shows considerable variation in isotopic composition in basalts along the Idaho Rift Zone. Two basalts from near Craters of the Moon have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios within the upper range of values for the Snake River olivine tholeiites. One of these basalts (69-22) was erupted through Paleozoic strata in the Pioneer Mountains north of the Monument; the other basalt (69-28) erupted from the rift zone along the eastern margin of the Craters of the Moon lava field less than 2080 years ago. (This flow is younger than the Holocene flow dated by Bullard and Rylander [40].) These basalts have major element and trace element compositions that are transitional between the Snake River tholeiites and COM-type basalts [31], and they may represent olivine tholeiite magma that experienced only minor shallow fractionation prior to eruption.

The Rb-Sr data are plotted in a conventional iso-

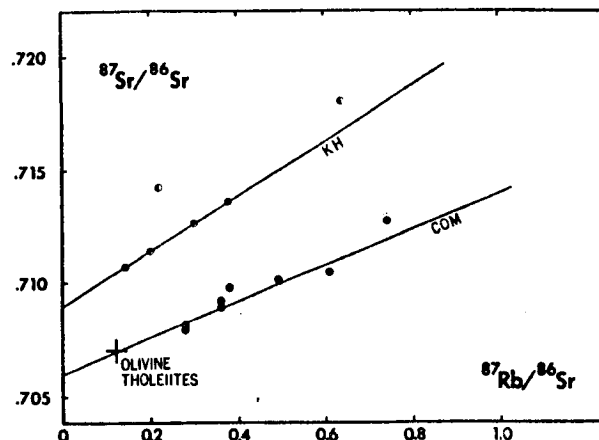


Fig. 5. Rb/Sr isochron diagram for Craters of the Moon (COM) and King Hill (KH) lavas. Ages and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicated are as follows: COM: age = 570 my, $R_0 = 0.706$; KH: age = 870 my, $R_0 = 0.709$. These apparent isochrons are interpreted as mixing-lines for magmatic Sr and radiogenic crustal Sr. Two highly evolved COM samples (69-19 and 69-20) were excluded on the assumption that their high $^{87}\text{Rb}/^{86}\text{Sr}$ ratios (1.02 and 1.43, respectively) developed by differentiation subsequent to contamination.

chron diagram (fig. 5), in which the Craters of the Moon basalts define a pseudo-isochron with an apparent age of 570 my and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.706. We interpret the pseudo-isochron as a mixing line for magmatic and crustal Sr. Two latites (69-19 and 69-20) do not lie on the line and we assume that their high Rb/Sr ratios resulted from differentiation effects subsequent to contamination. Contamination by old crustal rocks, e.g. Precambrian metamorphic rocks in the Albion Range with $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 0.806 and 1.465 [18] could explain the observed isotopic compositions in Craters of the Moon basalts. Bulk assimilation of only 5 weight percent of average Albion Range metamorphic rocks (150 ppm Sr, $^{87}\text{Sr}/^{86}\text{Sr} = 0.85$) by olivine tholeiite magma (270 ppm Sr, $^{87}\text{Sr}/^{86}\text{Sr} = 0.707$) will produce a mixture with 264 ppm Sr and $^{87}\text{Sr}/^{86}\text{Sr} = 0.7111$.

Two gneissic xenoliths from Craters of the Moon have higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than basalts from the same area. Their Rb contents and Rb/Sr ratios are rather low for such silicic rocks, perhaps indicating mobilization of Rb by partial fusion or diffusion from the xenoliths. The host basalts have not been analyzed and the degree of isotopic exchange, if any, between

host and xenolith cannot be evaluated at this time. However, large amounts (> 25% by weight) of this gneiss are required to account for the isotopic compositions of Craters of the Moon lavas by bulk contamination of olivine tholeiite magma; this is inconsistent with the bulk chemistry of the host basalts.

The King Hill lavas are notable because of their variability in isotopic composition, even within flows. A latite from King Hill has the highest $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (0.7180) observed in the Snake River Plain volcanic rocks. No simple explanation for their high and variable ratios is readily evident, since King Hill lavas occur near the middle of the Snake River Plain where seismic evidence indicates that silicic crust is thin if not absent. H.E. Malde, however, believes these lavas flowed south from a vent located in Cretaceous (?) granitic rocks near the north margin of the plain (personal communication). When the King Hill data are plotted on an isochron diagram (fig. 5) four of the six samples define a pseudo-isochron with an apparent age of 870 my and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.709. We interpret this apparent isochron as a contamination mixing line. However, this line does not pass through the olivine tholeiite field indicating that compositions of the King Hill lavas, if derived from Snake River tholeiite magma, cannot be explained by simple petrogenetic models.

7.3. Silicic volcanic rocks

Five Pliocene (Idavada Volcanics) silicic volcanic rocks from the Snake River Plain have isotopic compositions (0.7110–0.7134) similar to those of the Snake River COM-type basalts. Four of these rocks are welded tuffs from margins of the Snake River Plain; the other is a vitrophyre which underlies Snake River basalts at Shoshone Falls. Although the silicic volcanic rocks may underlie large portions of the Plain, they are not a likely source of Sr contamination for the COM-type lavas. The high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the silicic volcanics do not support a mantle origin for these rocks, and it is postulated that they were produced by remobilization of crustal rocks during formation of the Snake River depression.

8. Conclusions

Olivine tholeiites from the Snake River Plain have

uniformly high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7070 ± 0.0003 (2σ) which, if representative of their source in the mantle, indicates fundamental differences in composition between oceanic and some continental mantle regions. Comparison with other continental tholeiites suggests that, as an approximation, a minimum time-integrated Rb/Sr ratio of 0.04 is characteristic of many sub-continental mantle regions. This value is higher than the Rb/Sr ratio (0.025) inferred for oceanic regions from average modern-oceanic basalt data, but agrees well with that inferred from potassic oceanic-island basalts.

Comparison of strontium-isotopic data for late Cenozoic basalts from the western United States reveals significant regional variations. High $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (≥ 0.705) are observed in predominantly tholeiitic basalts from the Snake River Plain, Yellowstone Park [3,34,41], and the Columbia River Plateau [42], although Hedge et al. [43] report values of 0.703–0.704 in some Columbia River basalts (Picture Gorge variety). In contrast, predominantly alkali-olivine basalts from the Basin-Range Province and Colorado Plateau [9,15,44,45] have lower ratios (0.703–0.705). These regional variations in isotopic composition may reflect lateral variations in mantle isotopic composition or they may be related to differences in regional tectonic style and in the depth and mode of magma production in a vertically differentiated mantle.

Lavas from Craters of the Moon appear to be derived from Snake River olivine tholeiite magma by combined processes of fractional crystallization [31] and crustal contamination. Similar lavas from near King Hill appear to be derived from a different parent magma or from highly modified olivine tholeiite magma. Bulk assimilation of 5–10 percent of Precambrian basement rocks with high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios may explain the observed variations in isotopic composition of the Craters of the Moon lavas, but greater degrees of bulk contamination seem incompatible with major and trace element data. Other mechanisms, such as selective isotopic contamination, may have played an important role.

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