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GEOCHRONOLOGY AND GEOCHEMISTRY OF PLEISTOCENE BASALTS OF THE WESTERN SNAKE RIVER PLAIN AND SMITH PRAIRIE, IDAHO

KURT L. OTHBERG }
BILL BONNICHSEN } *Idaho Geological Survey, University of Idaho, Moscow, ID 83844–3014*
CARL C. SWISHER III *Geochronology Laboratory, Institute of Human Origins, Berkeley, CA 94709*
MARTHA M. GODCHAUX *Department of Geography and Geology, Mount Holyoke College, South Hadley, MA 01075–1484*

Previous study of the Pleistocene geology in the Boise Valley area defined the stratigraphy of terrace gravels and basalt flows emplaced on those terraces. New K/Ar and $^{40}Ar/^{39}Ar$ analyses and paleomagnetic measurements for the basalts are presented in this paper and establish a geochronology. Chemical similarities suggest several possible correlations. Several flows in the Indian Creek zone of basalts with similar chemical signatures and excursional to reverse paleomagnetic directions have $^{40}Ar/^{39}Ar$ ages that bracket the Cobb Mountain Normal Polarity Subchron. Based on chemistry and paleomagnetic polarities, the Steamboat Rock Basalt of Smith Prairie may correlate with these Indian Creek units. If so, some of the Steamboat Rock Basalt flows traveled about 100 km from their source down the ancestral Boise River. Based on paleomagnetic polarity, chemistry, and stratigraphy, two Smith Prairie units, the basalt of Smith Prairie and the upper unit of the basalt of Long Gulch, may correlate with the basalts of Gowen terrace and Lucky Peak, respectively, both located near the city of Boise, a flow travel distance of about 60 km. Major element chemical analyses reported here reveal an increase in potassium as the age of the basalt units decreases. Assimilation of granitic material probably was an important cause of late-stage alkali enrichment, but different basalt sources probably also contributed to the chemical variability of the basalts erupted in the western Snake River Plain graben and in the Smith Prairie area.

Eruptions of basalt in the western Snake River Plain (SRP) of Idaho (fig. 1) have been the primary form of volcanism throughout its eleven to sixteen million year history of rifting (Ekren and others, 1984; Malde, 1991; Wood, 1994). Before two million years ago the western SRP was an actively subsiding basin in which lake and fluvial sediments accumulated and were intercalated with basaltic lava flows, tephras, and phreatomagmatic deposits (Jenks and Bonnichsen, 1989; Malde, 1991; Godchaux and others, 1992; Othberg, 1994; Wood, 1994). Subsequently, the western SRP was deeply incised into canyons and broad, terraced river valleys. Incision and terracing occurred during pulses of glacial climate during the Pleistocene (Othberg, 1994). During this period, basaltic volcanism continued in the region and included eruptions in Smith Prairie, northeast of the western SRP (Howard and others, 1982). The basalt eruptions are characterized by subaerial lava flows that formed shield volcanoes, thick canyon fills, and thin flows that spread across broad alluvial valleys. At least two eruptions of basalt from Smith Prairie flowed 60 km or more down the Boise River canyon and onto the broader alluvial surfaces in the western SRP.

These geologic relationships have provided an opportunity to combine studies of terraces and basalt flows (Othberg, 1994). Here we describe the K/Ar and $^{40}Ar/^{39}Ar$ analyses, paleomagnetic measurements, and major-element geochemistry of the basalts. We also postulate some correlations between Smith Prairie and western SRP basalts, and interpret the changes in basalt composition over time in the western SRP.

STRATIGRAPHY

THE TERRACE SEQUENCE

Pleistocene gravel terraces of the ancestral Boise River are best preserved south of the city of Boise in the eastern part of the Boise Valley (fig. 2). The sequence there, in decreasing age, is the Tenmile terrace, the Amity terrace, the Fivemile Creek surface[1], the Lucky Peak surface, the Gowen terrace, the Sunrise terrace, the Whitney terrace, and the Boise terrace, which lies just above the floodplain of the Boise River. The sequence in the western part of the valley is less complete, but mantling by Bonneville Flood sediments provides a minimum age of 14,500 years for the terrace sequence (Othberg, 1994).

The oldest terrace in the Boise Valley, the Tenmile terrace, is composed of the Tenmile Gravel which overlies fine-grained late Pliocene basin-fill sediments locally correlated with the Glenns Ferry Formation. Stratigraphically, the Tenmile Gravel is younger than the Glenns Ferry Formation but predates the onset of

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[1] "Surface" is used where the terrace gravels have been completely buried by valley-filling basalt flows.

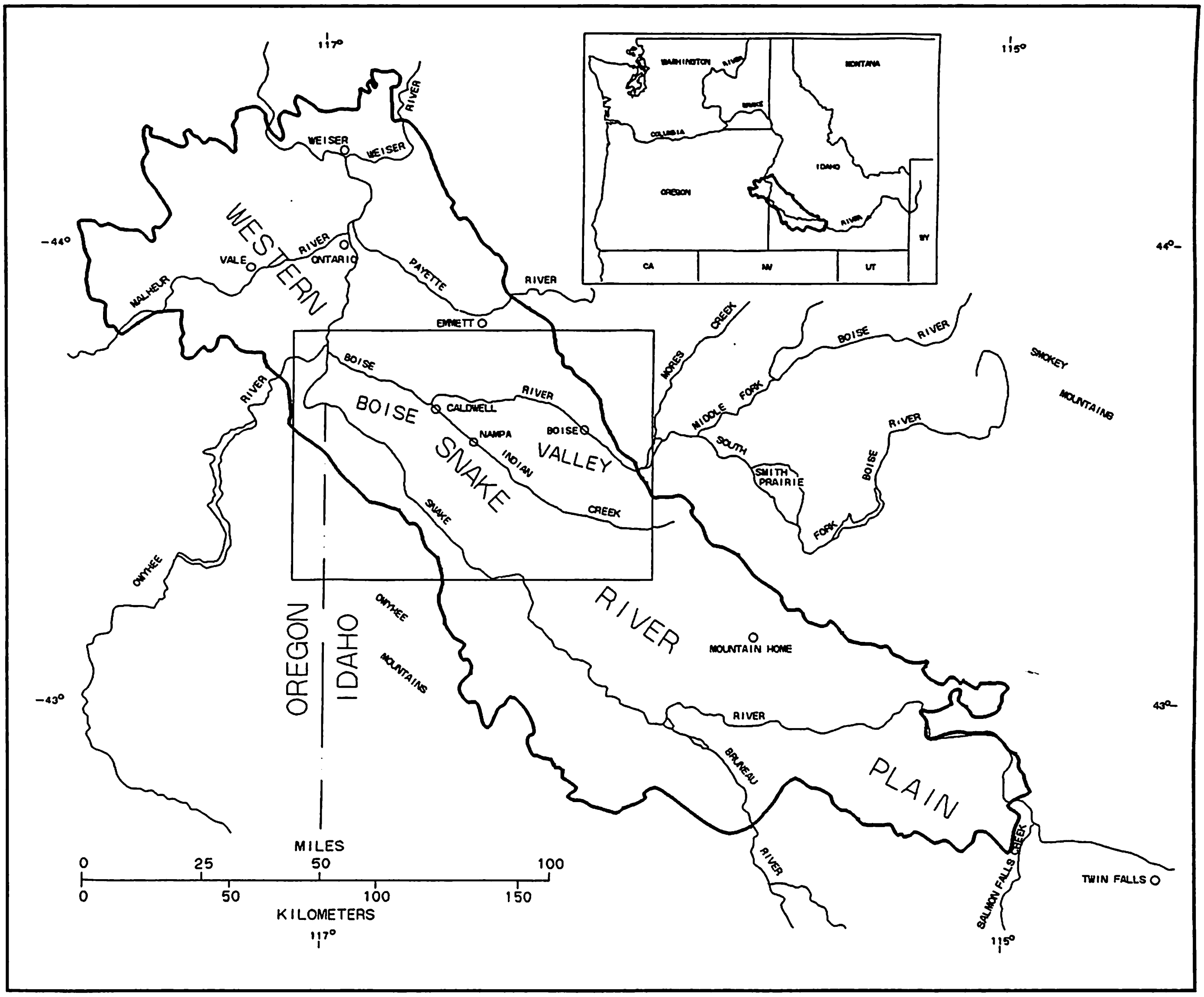

FIGURE 1. Location of the Boise Valley within the Western Snake River Plain. The rectangle inside the map encloses the area shown in figure 2. Inset: location of the western Snake River Plain in the Pacific Northwest.

episodic incision that was typical during the Pleistocene. The upper part of the Glenns Ferry Formation is probably younger than 1.76 Ma, the age of the latest geomagnetic polarity reversal of the Olduvai Normal Polarity Subchron (Van Domelen and Rieck, 1992; Cande and Kent, 1992), but younger than 0.9 Ma based on the presence of an immigrant microtine rodent that is an indicator species for Irvingtonian time (Ted Weasma and Charles A. Repenning, oral and written communication, 1992-1993).

All succeeding terrace gravels are younger than the Tenmile Gravel but at least as old as the Bonneville Flood sediments. The latest recorded event of the Pleistocene in the Boise Valley was the Bonneville Flood at 14,500 ka (Currey, 1990, O'Connor, 1993). As the catastrophic flood waters were hydraulically ponded behind Hells Canyon, fine-grained slackwater sediments were deposited within the western part of the Boise Valley and similar valleys in the western SRP. These thin-bedded silts of the Bonneville Flood mantle the lower three terraces within the western Boise Valley where the inundation occurred (fig. 3).

The 14,500-year age of the Bonneville Flood provides a minimum date for the terrace sequence and the soil developed on the surface of the Bonneville Flood sediments. Soil characteristics suggest that the youngest terrace in the sequence, the Boise terrace, is about the same age as the Bonneville Flood sediments, and therefore is a late Wisconsin terrace (Othberg, 1994).

Based on the soils developed on the eight terraces and the stratigraphic relationship of the gravels to the Bonneville Flood deposits and the Glenns Ferry Formation, the ages of the terraces in the Boise Valley appear to span the entire Pleistocene.

BASALTS EMPLACED ON TERRACES

Shield volcanoes, basaltic cones and lava flows form much of the surface of the western SRP south and southeast of the Boise valley. Several of the basalt lavas flowed into the Boise Valley (fig. 4). Othberg (1994) describes the sources of these flows and their emplacement on terraces. Howard and Shervais (1973), Howard and others (1982), and Vetter and Shervais (1992) provide stratigraphy, dates, and chemical analyses for basalts that originated in Smith Prairie.

The Boise River canyon near Lucky Peak Dam exposes basalts that bury Pleistocene terrace gravels (fig. 5). One unit is the basalt of Lucky Peak named by Howard and others (1982) for a single thick flow just downstream from Lucky Peak Lake. The other unit, locally called the basalt of Gowen terrace, was correlated by Howard and others (1982) with the Steamboat Rock Basalt in Smith Prairie. However, new K/Ar dating and differences in paleomagnetic polarities reported here cast doubt on the correlation (Othberg and Burnham, 1990; Othberg, 1994). The other two basalts shown in figure 5 are the late Pleistocene basalt of Mores Creek and the early Pleistocene basalt of Fivemile Creek.

Other basalts flowed into Pleistocene drainageways south of Lake Lowell. Hat, Pickles, Powers, and Kuna Buttes were sources for many of these flows (fig. 4). Othberg (1994) surmised that possible sources of basalts that flowed down valley(s) ancestral to the present drainage of Indian Creek were vents to the southeast in the central ridge area of the plain where Christmas Mountain is located (fig. 4). Another possibility, described in this paper, is that at least some of the Indian Creek lavas originated in Smith Prairie and flowed as far as 100 km down the ancestral Boise River.

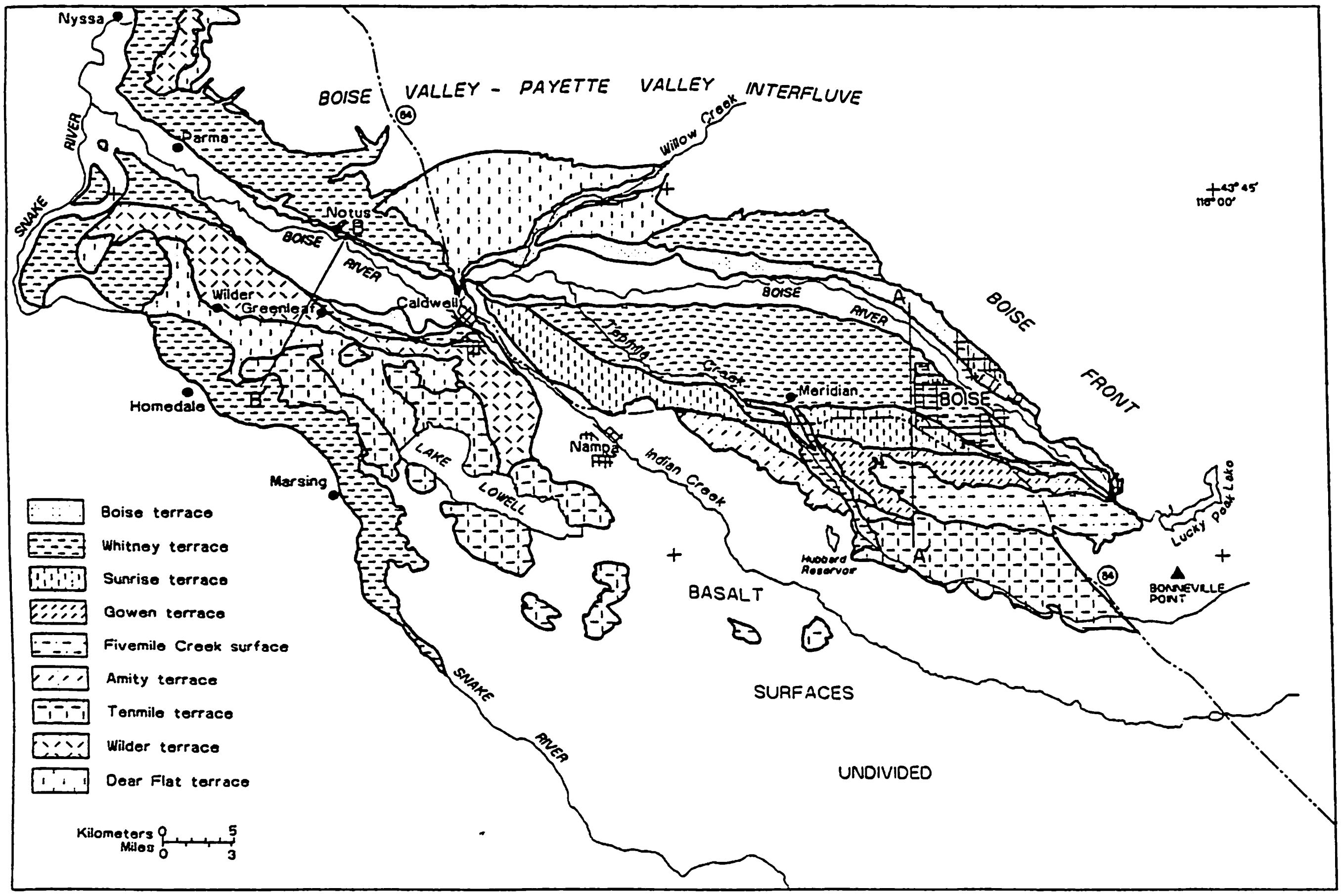

FIGURE 2. Distribution of Boise Valley terraces. Lines A-A′ and B-B′ show the approximate locations of the east and west diagrammatic profiles in figure 3.

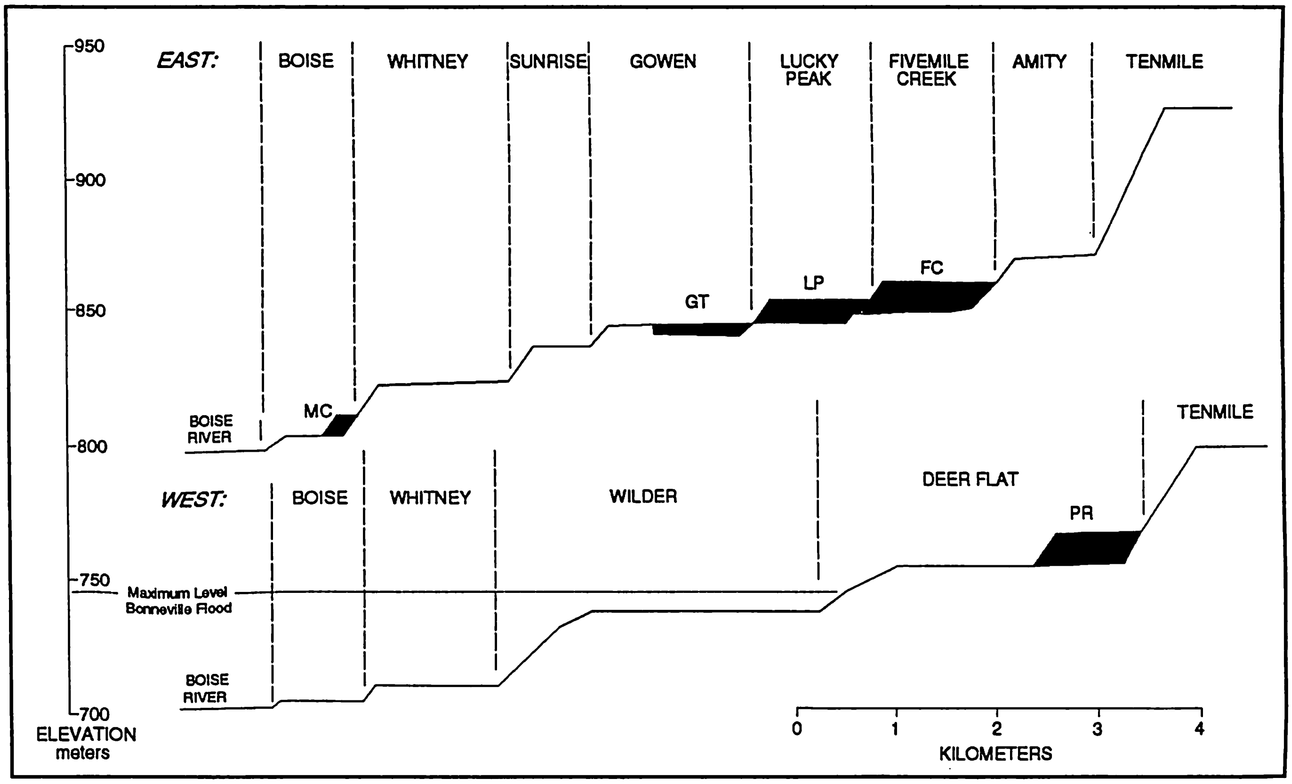

FIGURE 3. Diagrammatic profiles of the eastern and western Boise Valley terraces and terrace-capping basalt flows. In the western sequence the Boise, Whitney, and Wilder terraces were mantled with Bonneville Flood sediments, the level of which is indicated. Basalt flows are MC, basalt of Mores Creek; GT, basalt of Gowen terrace; LP, basalt of Lucky Peak surface; FC, basalt of Fivemile Creek surface; and PR, basalt of Pickles rim surface.

ANALYTICAL PROCEDURES AND RESULTS

K/Ar AND $^{40}Ar/^{39}Ar$ DATING

Samples of basalt flows collected early in the field work were analyzed for K/Ar ages; basalt samples collected later were analyzed for $^{40}Ar/^{39}Ar$ ages. All radiometric dating was done at the Geochronology Laboratory, Institute of Human Origins, Berkeley, California.

The K/Ar dates (table 1) are the result of whole-rock analyses in which each sample was run at least twice. The samples were crushed, sieved, and washed in distilled water. The 60-100 mesh size was then treated with dilute (10%) HCl, dilute (7%) HF, rinsed with distilled water, then boiled in distilled water for approximately one hour. After the samples were loaded on the extraction line, they were baked out at 120°C overnight. The potassium values in table 1 are the average of three analyses using flame photometry.

TABLE 1. Potassium-argon ages based on whole rock analyses. Decay constants are as follows (also for table 2); $\lambda_\varepsilon+\lambda_{\varepsilon'} = 0.581 \times 10^{-10} yr^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10} yr^{-1}$; $\lambda = 5.543 \times 10^{-1} yr^{-1}$; and $^{40}K/K_{total} = 1.167 \times 10^{-4}$; $^{40}Ar^*$ refers to radiogenic component.

Rock unit	KA number	Sample number	$\%K^+$	Weight (grams)	$^{40}Ar^*$ (mol/gm)	$\%^{40}Ar^*$	Age ± 1σ (Ma)
Basalt of Mores Creek	5838B-2	MC-1	1.397	6.56930	2.588×10^{-13}	9.0	0.107 ± 0.012
Basalt of Gowen terrace	5937-1	GT-4	0.945	7.01441	9.369×10^{-13}	8.3	0.572 ± 0.210
Basalt of Slaters Flat	5935-1	7-18-85-1	0.524	2.96297	8.243×10^{-13}	3.6	0.907 ± 0.280
Basalt of Fivemile Creek	5934-1	30-3	0.532	4.22543	8.987×10^{-13}	11.2	0.974 ± 0.130
Basalt of Hubbard Reservoir	5837B-1	TCC-1	0.864	5.12164	1.500×10^{-12}	5.8	1.001 ± 0.098
Basalt of Lucky Peak	5936-1	LP-4	0.490	7.65444	1.160×10^{-12}	3.7	1.364 ± 0.210

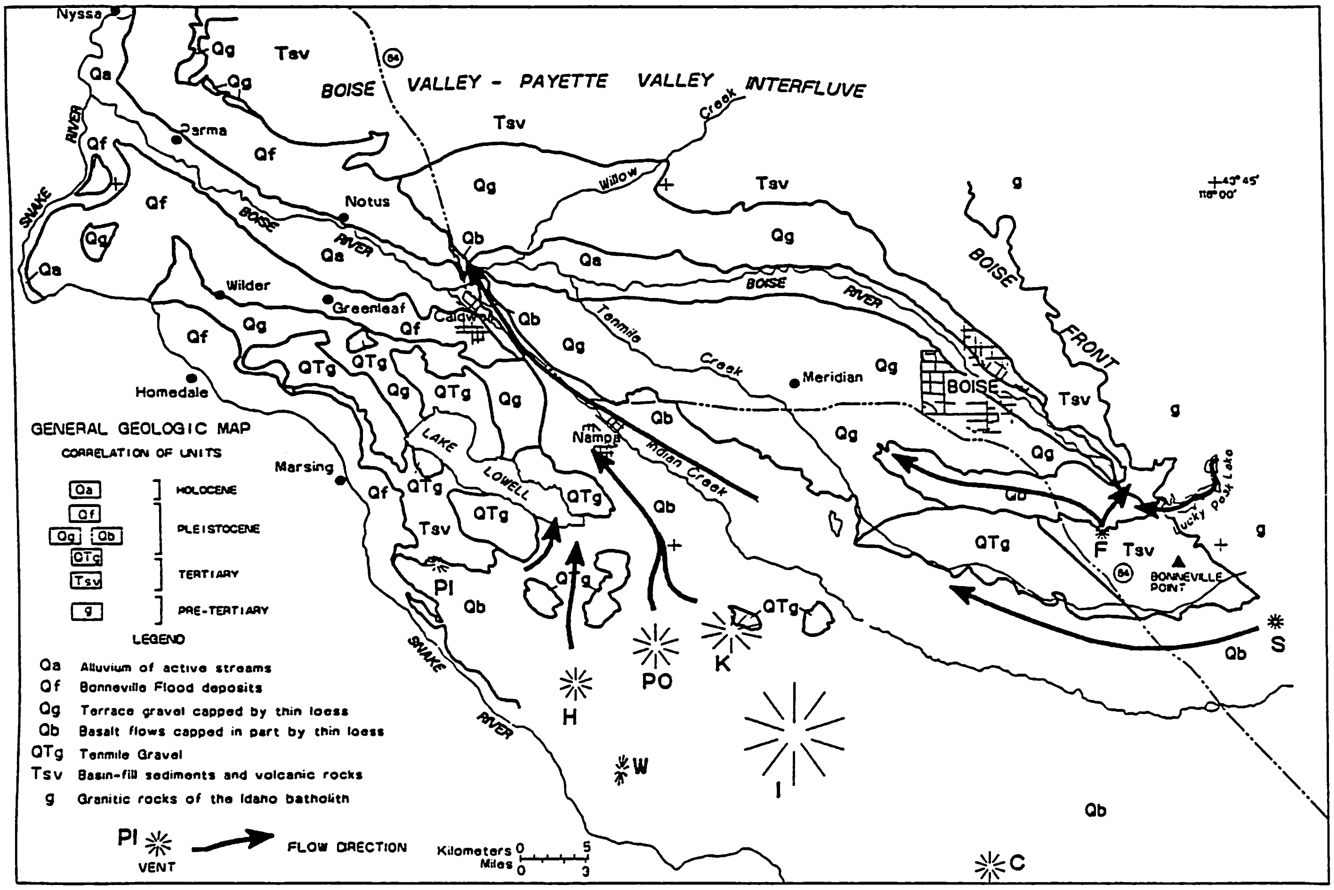

FIGURE 4. Locations of selected volcanic vents and flow directions of basalt flows emplaced on terraces of the Boise Valley: C, Christmas Mountain; F, Fivemile Creek; H, Hat Butte; I, Initial Point; K, Kuna Butte; PI, Pickles Butte; PO, Powers Butte; S, Slaters Flat; W, Walters Butte.

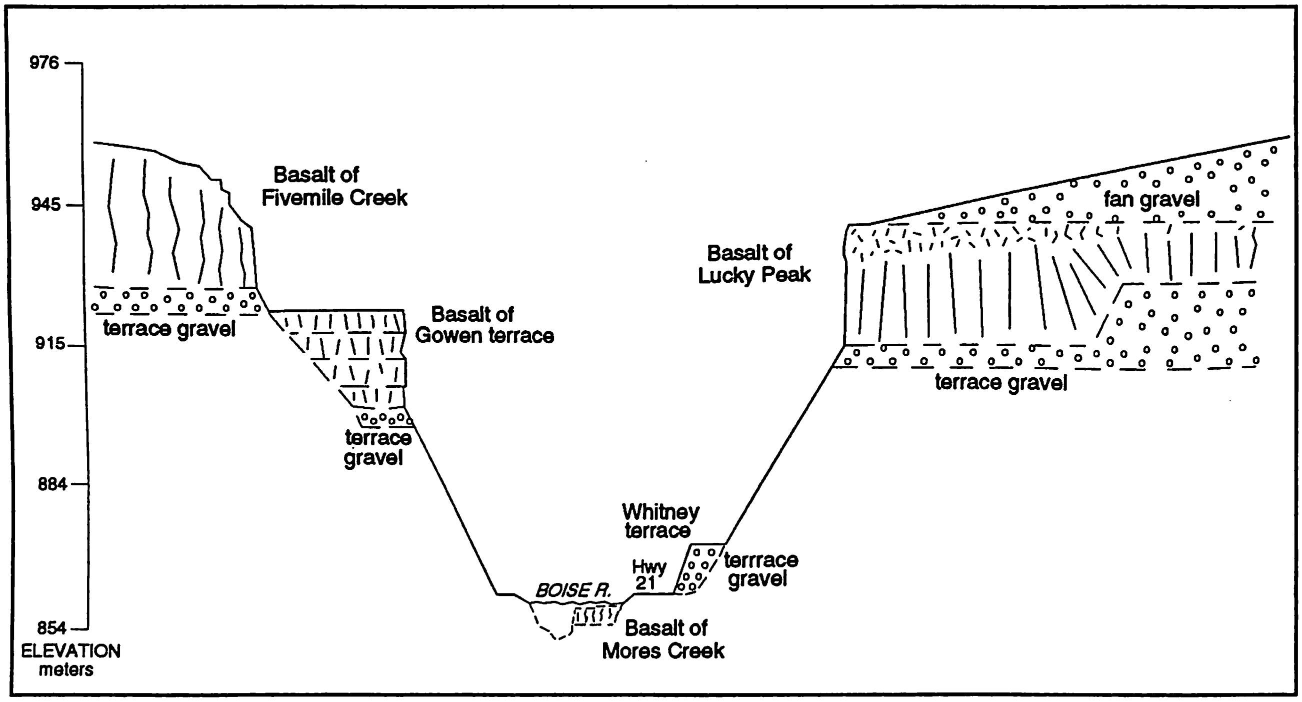

FIGURE 5. Profile and cross section of the Boise River canyon near Lucky Peak Dam showing stratigraphy of lava flows and buried terrace gravels. Stratigraphy of basalt units, oldest to youngest: basalt of Fivemile Creek, basalt of Lucky Peak, basalt of Gowen terrace, and basalt of Mores Creek.

TABLE 2. $^{40}Ar/^{39}Ar$ incremental laser heating analyses. Step is the laser watt output. J = 0.0099585 ± 0.0000058. Age is in Ma. SD = standard deviation.

Sample	L#/Step	37/39	36/39	40*/39	% Rad.	Age	SD
SS3	4860-01A	3.42775	4.14349	-30.49799	-2.5	-17.835	17.262
	4860-01B	1.83493	0.17607	-0.16139	-0.3	-0.094	0.394
	4860-01C	1.13096	0.01936	0.24275	4.1	0.141	0.053
	4860-01D	0.79749	0.00365	0.56245	35.5	0.327	0.044
	4860-01E	0.89201	0.00296	0.81483	50.1	0.474	0.110
	4860-01F	2.16564	0.00480	0.58942	31.9	0.343	0.119
	4860-01G	6.42496	0.01051	0.50085	16.0	0.291	0.246
					Plateau age =	**0.387**	**0.031**
IP3	4864-01A	4.13663	3.24197	55.82182	5.5	32.194	29.136
	4864-01B	2.28457	0.73532	3.48400	1.6	2.026	1.605
	4864-01C	1.56944	0.02681	0.75450	8.8	0.439	0.226
	4864-01D	1.17626	0.00696	0.64997	24.8	0.378	0.051
	4864-01E	1.20845	0.00318	0.72112	45.9	0.420	0.063
	4864-01F	5.07117	0.00878	0.65279	22.7	0.380	0.129
	4864-01G	22.55704	0.02824	1.01344	13.1	0.590	0.287
					Plateau age =	**0.414**	**0.037**
CBR	4862-01A	1.28646	1.78516	0.22020	0.0	0.128	5.365
	4862-01B	1.11350	0.24404	0.70688	1.0	0.411	0.667
	4862-01C	2.12274	0.11766	0.46689	1.3	0.272	0.280
	4862-01D	2.92125	0.06610	1.14258	5.6	0.665	0.239
	4862-01E	4.37139	0.04451	1.37585	9.7	0.800	0.116
	4862-01F	13.07923	0.09968	1.61242	5.3	0.938	0.272
	4862-01G	21.44473	0.08591	1.28118	5.0	0.745	0.471
					Plateau age =	**0.799**	**0.095**
UDF4	4859-01A	0.73464	0.34833	-2.86153	-2.9	-1.666	1.523
	4859-01B	0.66928	0.23681	-1.04545	-1.5	-0.609	0.553
	4859-01C	0.90876	0.16822	1.79263	3.5	1.043	0.335
	4859-01D	1.62963	0.18034	1.37545	2.5	0.800	0.378
	4859-01E	3.19765	0.17805	1.61369	3.0	0.939	0.386
	4859-01F	14.39340	0.11559	1.34093	3.9	0.780	0.533
	4859-01G	23.77381	0.07714	1.86597	8.0	1.086	0.551
					Plateau age =	**0.922**	**0.184**
NSS	4863-01A	0.53797	0.71994	0.95439	0.4	0.555	2.208
	4863-01B	0.76928	0.20387	1.55954	2.5	0.907	0.430
	4863-01C	1.30512	0.12179	1.63537	4.4	0.951	0.216
	4863-01D	2.11846	0.08925	1.95047	6.9	1.135	0.317
	4863-01E	3.68661	0.06437	2.58775	12.1	1.505	0.248
	4863-01F	9.96875	0.05093	1.98680	12.1	1.156	0.337
	4863-01G	21.84204	0.04294	1.93969	14.8	1.128	0.781
					Plateau age =	**1.165**	**0.125**
AM4	4858-01A	0.71923	0.70117	6.50365	3.0	3.780	4.357
	4858-01B	0.72141	0.25318	2.24398	2.9	1.305	0.662
	4858-01C	1.40594	0.09940	2.17674	6.9	1.266	0.213
	4858-01D	2.51040	0.06071	1.90355	9.7	1.107	0.191
	4858-01E	5.68767	0.05643	1.89779	10.4	1.104	0.432
	4858-01F	14.20530	0.05452	2.38474	13.6	1.387	0.335
	4858-01G	21.28444	0.02604	4.99993	44.7	2.907	0.756
					Plateau age =	**1.231**	**0.123**
IC2	4866-01A	1.59775	0.37838	4.33529	3.7	2.521	1.958
	4866-01B	0.94185	0.21909	-0.98305	-1.5	-0.572	1.614
	4866-01C	1.38909	0.15900	1.00776	2.1	0.586	0.879
	4866-01D	1.98398	0.09645	2.15287	7.0	1.252	0.433
	4866-01E	4.06246	0.08146	2.28891	8.8	1.331	0.316
	4866-01F	13.45943	0.12132	2.53996	6.7	1.477	0.378
	4866-01G	23.50153	0.17697	2.62078	4.9	1.524	0.840
					Plateau age =	**1.376**	**0.205**
PR1	4865-01A	2.29366	0.99529	-4.15145	-1.4	-2.417	3.583
	4865-01B	1.36055	0.37825	-4.50835	-4.2	-2.625	0.814
	4865-01C	1.33159	0.04319	1.90633	13.1	1.109	0.295
	4865-01D	2.00228	0.00403	3.49310	77.0	2.031	0.173
	4865-01E	3.67936	0.00541	2.75092	67.5	1.600	0.131
	4865-01F	10.19967	0.01341	3.05477	48.7	1.777	0.168
	4865-01G	41.66791	0.03036	8.83674	59.6	5.135	0.725
					Plateau age =	**1.580**	**0.085**

The $^{40}Ar/^{39}Ar$ dates (table 2 and fig. 6) are based on analyses of the total fusion of individual whole-rock grains, 0.3 to 0.5 mm in size, from each sampled basalt. Argon extractions and isotopic analyses were conducted with a fully automated $^{40}Ar/^{39}Ar$ laser fusion-microextraction system. This extraction system is in-line with a Mass Analyzer Products MAP 215 mass spectrometer, operated at a 500 to 600 resolution. Argon backgrounds for this instrument are typically: $^{40}Ar \leq 2.0 \times 10^{-12}$ cm^3 (STP); $^{39}Ar \leq 5.0 \times 10^{-14}$ cm^3 (STP); $^{37}Ar \leq 7.0 \times 10^{-14}$ cm^3 (STP); $^{36}Ar \leq 2.0 \times 10^{-14}$ cm^3 (STP). The detection limit is on the order of 1.0×10^{-14} cm^3 (STP). Samples of whole-rock basalt were crushed or sliced to 0.5 to 1 cm. Fragments were then examined for xenolithic contamination. Contamination-free chips were crushed further, sieved (60 to 100 mesh), and washed. The samples were then treated with a 10% HCl solution and a 5% HF solution in an ultrasonic bath for 10 and 5 minutes, respectively, and then rinsed in distilled water in an ultrasonic bath for 5 minutes. From this material, approximately 250 whole-rock grains were picked for irradiation. Samples for irradiation were

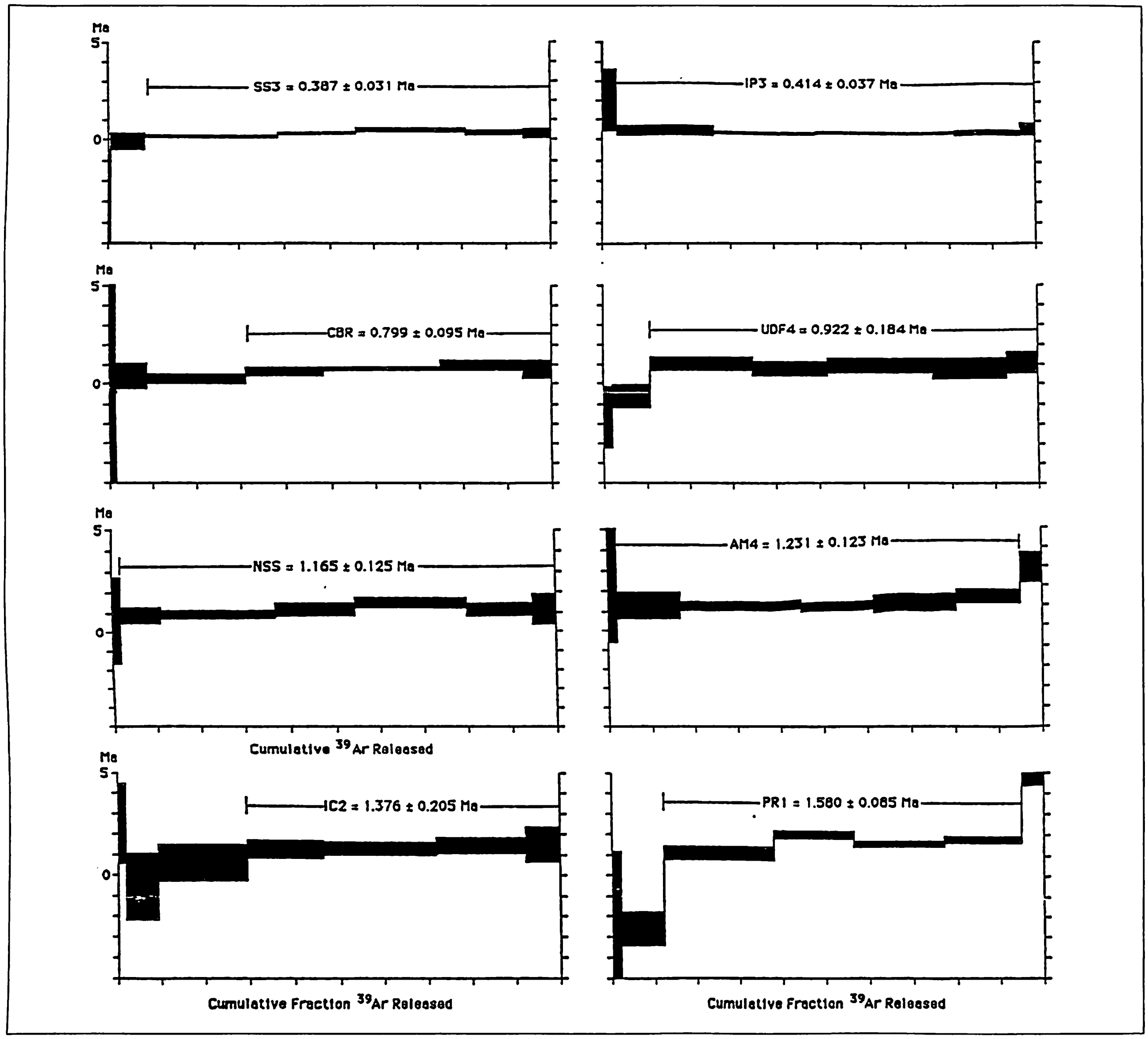

FIGURE 6. $^{40}Ar/^{39}Ar$ laser incremental heating spectra.

TABLE 3. Radiometric age, paleomagnetic polarity, and paleomagnetic directions for Pleistocene basalts of the Boise Valley and associated areas (DEC., paleomagnetic declination; INC., paleomagnetic inclination; N, number of samples; R, resultant vector; α_{95}, 95% confidence limit in degrees; k, estimated precision; paleomagnetic polarity — N, normal, R, reverse, E, excursional.

Basalt unit	Site	Lat.	Long.	Age (Ma)	Polarity	DEC.	INC.	N	R	α_{95}	k
Mores Creek	MC	43°31.52′	116°03.76′	0.107±0.012	N						
Gowen terrace	GT	43°31.33′	116°04.24′	0.572±0.210	N	6.7	62.3	4	3.99	6.2	219
Kuna Butte	SSB	43°31.51′	116°32.03′	0.387±0.031	N	22.4	60.8	8	7.74	10.9	27
Initial Point	IP	43°22.32′	116°23.61′	0.414±0.037	N						
Initial Point	1561	43°21.78′	116°24.78′		N	6.4	49.5	9	8.97	3.1	270
Christmas Mt.	CM	43°16.95′	116°12.67′		N						
Lucky Peak	LP	43°31.85′	116°03.66′	1.364±0.210	N	336.1	56.3	2	1.94	67.8	16
Long Gulch	LGU	43°32.31′	115°42.28′		N	344.8	60.6	5	4.97	6.5	141
Long Gulch	LGL	43°32.31′	115°42.28′		N	346.9	56.6	4	3.99	5.5	282
Caldwell	CBR	43°41.31′	116°41.06′	0.799±0.095	E or R?	55.4	-42.6	7	4.96	42.9	3
Up. Deer Flat	UDF	43°30.29′	116°34.38′	0.922±0.184	R	151.0	-29.2	7	6.89	8.3	54
Slaters Flat	SF	43°27.54′	115°58.93′	0.907±0.280	N	340.5	61.6	7	6.99	3.0	401
Fivemile Creek	30	43°32.67′	116°09.38′	0.974±0.098	N	337.7	59.2	7	6.93	6.4	89
Fivemile Creek	F	43°32.67′	116°09.38′		N	339.1	55.2	6	5.98	4.7	208
Fivemile Creek	PV	43°30.27′	116°06.91′		N	349.3	62.3	4	3.96	11.1	70
Fivemile Creek	HT	43°31.52′	116°04.45′		N	334.2	57.8	6	5.88	10.4	42
Hubbard Res.	TCC	43°31.92′	116°20.20′	1.001±0.098	N						
Mason Creek	AM	43°33.72′	116°28.23′	1.231±0.123	E or R?	280.6	-24.6	8	5.11	45.8	2
East Nampa	NSS	43°36.23′	116°31.12′	1.165±0.125	E or R?	88.6	-17.7	8	6.36	30.5	4
Black Cat Road	BC	43°31.43′	116°27.15′		R						
Kuna City	IC	43°29.13′	116°24.43′	1.376±0.205	E?	57.4	-62.7	6	5.90	9.4	52
Rawson Canal	RC	43°34.09′	116°27.12′		E?	62.6	0.0	7	6.92	7.1	73
Missouri Ave.	MI	43°28.74′	116°39.08′		R						
Pickles Butte	PR	43°28.03′	116°44.99′	1.580±0.085	R	227.8	-14.4	6	5.97	5.2	169
Steamboat Rock	SR	43°28.57′	115°37.77′		R	184.6	-59.7	5	4.98	5.0	235

encapsulated in aluminum cups and arranged in a known geometry along with mineral standards. The sample package was placed in a cadmium lined, 2.5 cm-diameter aluminum tube. Then the sample set was irradiated 10 minutes at 8 MW in the hydraulic rabbit of the Los Alamos National Laboratory Omega West reactor by fast neutrons to produce the reaction ^{39}K(n,p) ^{39}Ar. After irradiation, the samples were transferred to a copper sample holder and loaded into the Ar-extraction system. Fusion was induced by a 6-W continuous Ar-ion laser beam focused to a 2- to 3-mm spot, applied for 20 to 60 seconds. The gases released from the grains were then scrubbed for reactive species (CO_2, CO, and N_2) by exposure to a 150°C Zr-Fe-V alloy getter for 3 to 5 minutes. The remaining inert gases, principally Ar, were then admitted to the mass spectrometer, and the argon-isotopic ratios were determined. The mass spectrometer was operated in static mode with the use of automated data-collection procedures. The age is then calculated from the ^{40}Ar/^{39}Ar ration after all interfering Ar-isotopes from atmospheric contamination and undesirable neutron reactions with Ca and K are corrected.

PALEOMAGNETISM

The paleomagnetic polarities of selected basalt units were determined in the field using a portable flux-gate magnetometer and five samples per site (table 3). The paleomagnetism of twenty-two sites using field-oriented samples were analyzed in the laboratory. Paleomagnetic analyses were done at Eastern Washington University, Cheney, Washington; U.S. Geological Survey, Flagstaff, Arizona; and University of Idaho, Moscow, Idaho. Resulting declinations, inclinations, and Fisher statistics are shown in table 3.

Paleomagnetic directions from five units differ greatly from a dipole geomagnetic direction for this latitude (declination and inclination of 0 and 62, or

180 and -62), and may record one or more excursions of the geomagnetic field. Dispersion of directions from two of these units, Kuna City and Rawson Canal, are relatively low (α_{95} of 9.4 and 7.1, respectively). However, directions for the Caldwell, Mason Creek, and East Nampa lava flows are highly dispersed (α_{95} ranges from 30.5 to 45.8). Although an excursional geomagnetic field direction may have been present at the time of cooling of the Caldwell, Mason Creek and East Nampa basalts, an unstable magnetic component may be the cause of the large directional dispersion, effectively masking a reverse paleomagnetic direction. This could result from a younger normal polarity overprinting a reverse polarity signature, and the unstable normal-polarity component was not sufficiently removed by alternating field demagnetization in every sample. Normal overprinting was recognized at the Mason Creek site by the measurement of normal polarity in the field, but an excursional to reverse polarity after laboratory demagnetization. However, reverse polarity was obtained in the field at the Caldwell, East Nampa, and Kuna City sites. Adequate hand samples were unavailable for a field measurement at the Rawson Canal site.

GEOCHEMISTRY

Compositions of Dated Samples

Major element analyses are reported in table 4 for all of the newly dated units listed in table 3, with the exception of the basalts of Mores Creek and Hubbard Reservoir. Also, analyzed samples from the previously-dated (Howard and others, 1982) upper basalt of Long Gulch and Steamboat Rock Basalt, and the undated lower basalt of Long Gulch, all from the Smith Prairie area (Howard and Shervais, 1973), and the undated basalt of Mason Creek from the Boise Valley (table 3) are included in table 4.

Analytical Procedure

The samples listed in table 4 were analyzed by Bill Bonnichsen in 1991-93, using x-ray fluorescence spectrometry at the Ronald B. Gilmore Laboratory, Department of Geology and Geography, University of Massachusetts-Amherst. The analyses were performed in duplicate on La-bearing, lithium-tetraborate fused glass discs using modifications of the methods of Norrish and Hutton (1969). Prior to fusion, rock powders were ignited and oxidized in air at 1,000°C for 4 hours or more. Calibrations are based on natural and synthetic standards and total iron was analyzed as Fe_2O_3.

CONCLUSIONS

Figure 7 compares the magnetic polarities and the K/Ar and $^{40}Ar/^{39}Ar$ age ranges of the basalt units with the details of the magnetic polarity time scale for the late Pliocene and the Pleistocene.

The radiometric dates for the most part compare reasonably well with the known stratigraphic and geomorphic positions of the units. A major exception is the basalt of Lucky Peak, with a K/Ar age of about 1.4 Ma (table 1 and fig. 7). Stratigraphy and paleomagnetic polarity, however, indicate its age is bracketed by the Brunhes-Matuyama Polarity Chron boundary and the age of the basalt of Gowen terrace (figs. 5 and 7).

Lava flows that occur in the zone paralleling Indian Creek are difficult to separate in geologic mapping because of considerable loess and soil mantling. Four of the dated units in the Indian Creek zone, lava flows of Caldwell, East Nampa, Kuna City, and Mason Creek, however, are similar both petrographically and chemically, and record excursional to reverse paleomagnetic directions. The Caldwell and East Nampa units are nearly physically traceable to one another, and as valley-filling basalts, both form reversed topography of an ancestral river valley, probably that of the Boise River. The East Nampa, Kuna City, and Mason Creek units have $^{40}Ar/^{39}Ar$ ages that overlap in the range of 1.171-1.354 Ma. Caldwell's $^{40}Ar/^{39}Ar$ date of about .8 Ma is considerably younger, but all the other evidence (especially the chemically evidence) suggests correlation with the East Nampa unit. Therefore, the Caldwell date probably is too young.

The $^{40}Ar/^{39}Ar$ ages of the possible excursional paleomagnetic directions overlap the reported age of the Cobb Mountain Normal Polarity Subchron (fig. 7). The Indian Creek basalt units may have recorded some portion of the geomagnetic field changes that occurred during that period of time.

SOURCES AND POSSIBLE CORRELATIONS OF BASALT UNITS

The compositional similarity and excursional to reverse paleomagnetic directions for some basalt units in the Indian Creek zone suggest that the basalts of Caldwell, East Nampa, Kuna City, Mason Creek, and Rawson Canal erupted from a single source over a relatively short period of time. The lava source for these rocks in the Indian Creek zone is not too obvious. Based on today's physiography, one might look to the southeast in the central ridge of the western SRP for the source. However, chemical analyses of several basalt samples (B. Bonnichsen and M.M. Godchaux, unpublished data) from the central ridge of the western

TABLE 4. Major element compositions of samples for which age dates are reported. These analyses were made by x-ray fluorescence methods, as described in the text. The Mg/(Mg+Fe) ratios are atom percentages.

Basalt unit	Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Mg/ (Mg+Fe)
Kuna Butte	KO-SS	48.66	2.25	16.30	11.83	0.18	6.17	8.85	3.46	1.85	0.73	100.28	50.8
Initial Point vent	KO-IP	47.71	2.08	15.81	12.20	0.18	7.70	9.72	2.92	1.41	0.44	100.17	55.6
Gowan terrace	KO-GT-4	47.52	2.11	15.86	13.33	0.19	7.26	9.67	2.87	1.06	0.44	100.31	51.9
Lucky Peak	KO-LP-7	45.68	3.12	14.36	15.67	0.21	7.14	9.75	2.53	0.66	0.80	99.92	47.4
Upper Long Gulch	KO-LGU-4	45.83	3.28	14.28	16.25	0.22	6.32	9.08	2.71	1.02	0.80	99.79	43.5
Lower Long Gulch	KO-LGL-6	48.23	3.12	14.18	16.37	0.25	3.72	6.91	3.30	2.35	1.23	99.66	31.0
Caldwell	KO-CBR	46.07	3.00	14.61	15.39	0.21	7.23	9.63	2.77	0.62	0.60	100.13	48.2
Slaters Flat	KO-SF-4B	45.44	3.58	13.56	16.95	0.24	6.49	9.67	2.53	0.59	0.85	99.90	43.1
Upper Deer Flat	KO-UDF	44.61	3.45	13.46	16.65	0.23	6.91	11.03	2.59	0.56	0.88	100.37	45.1
Fivemile Creek	KO-30-5	46.08	3.31	14.18	16.43	0.23	6.73	9.49	2.61	0.59	0.72	100.37	44.8
Fivemile Creek	KO-PV-4	45.63	3.39	13.84	16.52	0.23	6.71	9.82	2.48	0.55	0.76	99.93	44.6
Fivemile Creek	KO-HT-1	45.94	3.33	14.07	16.48	0.23	6.64	9.56	2.66	0.58	0.72	100.21	44.4
Mason Creek	KO-AM	46.11	3.15	14.31	15.72	0.21	6.98	9.61	2.63	0.59	0.59	99.90	46.8
East Nampa	KO-NSS	46.18	2.94	14.59	15.19	0.21	7.13	9.71	2.79	0.60	0.61	99.95	48.2
Kuna City	KO-IC	45.59	3.31	14.51	16.08	0.22	6.81	9.88	2.57	0.50	0.59	100.06	45.6
Rawson Canal	KO-RC	45.81	2.98	14.28	15.17	0.21	7.04	10.87	2.62	0.57	0.60	100.15	47.9
Pickles Butte	KO-PR	45.82	3.58	13.86	16.79	0.23	6.34	9.42	2.69	0.67	0.75	100.15	42.8
Steamboat Rock	KO-SR-3	45.79	2.98	14.95	15.24	0.20	7.08	9.94	2.56	0.57	0.58	99.89	47.9

SRP are distinct from the basalts in the Indian Creek zone. The similarity in TiO_2, Fe_2O_3, MgO, and P_2O_5 for the basalts of Caldwell, East Nampa, and Rawson Canal with the Steamboat Rock Basalt suggests a source in the Smith Prairie area. The K/Ar date of 1.8±0.3 Ma for Steamboat Rock Basalt (Howard and others, 1982) would preclude this correlation, but additional evidence suggests otherwise. Steamboat Rock Basalt is composed of numerous pahoehoe flows with a cumulative original volume of several cubic kilometers (Howard and others, 1982). It is not unreasonable to suggest that some of these flows followed the Boise River valley as far as the present location of Caldwell, some 100 km downstream from Smith Prairie. The distributions of early Pleistocene terrace gravel deposits and subsequent basalt flows show that the course of the ancestral Boise River shifted northward primarily in response to the emplacement of valley-filling basalts. The Steamboat Rock Basalt has not been traced into the western SRP[1], but flow remnants may be buried under the younger and extensive basalt of Fivemile Creek. This would be a reasonable location for an early Pleistocene course of the ancestral Boise River, which had previously been diverted northward into the Nampa-Caldwell area by eruptions in the vicinity of Hat Butte and Pickles Butte and by tectonic subsidence in the Nampa-Caldwell basin (Wood and Anderson, 1981; Malde, 1991; Othberg, 1994). Furthermore, a flow in the upper part of the Steamboat Rock Basalt records a reverse-polarity paleomagnetic direction that is nearly coincident with a dipole geomagnetic direction (table 3). The basalt units in the Indian Creek zone record reverse or excursional paleomagnetic directions. If Steamboat Rock Basalt erupted over a long enough period of time, then excursional directions may have been recorded by some of the many flows in the formation. In fact, Howard and others (1982) reported field measurements of normal magnetic polarity for the Steamboat Rock Basalt. Further paleomagnetic study and radiometric dating of the Steamboat Rock Basalt seems warranted, especially if the period of eruptions encompassed a geomagnetic field reversal.

It is possible that the basalt of Lucky Peak is the same unit as the upper basalt of Long Gulch, based on their normal paleomagnetic polarities and generally similar compositions, except for K_2O. If this is true, and if Howard and others (1982) 0.68 Ma age for the upper basalt of Long Gulch is accurate (rather than the 1.364 Ma age that we report for the basalt of Lucky Peak),

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[1] Howard and others (1982) suggested the basalt of Gowen terrace correlated with the Steamboat Rock Basalt, but subsequent study has shown the basalt of Gowen terrace to be much younger (Othberg and Burnham, 1990, Othberg, 1994).

the basalt of Lucky Peak would neatly fit into the time interval between the older basalt of Fivemile Creek and the younger basalt of Gowan Terrace, which is exactly where the Lucky Peak unit is situated in the terrace stratigraphy (fig. 5).

The basalt of Gowan Terrace shares normal paleomagnetic polarity and similar composition to two Smith Prairie units (Vetter and Shervais, 1992), the basalt of Lava Creek and the basalt of Smith Prairie. If the Gowan Terrace unit had its source in the Smith Prairie area it most likely correlates with the more voluminous basalt of Smith Prairie, inasmuch as Howard and Shervais (1973) geologic map indicates that the Lava Creek unit did not flow as far as the canyon of the Boise River. Also, the 0.20 and 0.26 Ma ages reported by Howard and others (1982) for the basalt of Smith Prairie more closely matches the stratigraphic position of the basalt of Gowan Terrace in the Boise River Canyon, and the relatively large precision limits for the K/Ar dates overlap (figs. 5 and 7).

CHANGE IN BASALT COMPOSITION WITH TIME

From the age versus percent potassium plot (fig. 8) it is clear that the youngest basalt units generally have the greatest abundances of potassium. Not only is this true for the basalts investigated in this study, but it is true for many other basalt flows in the central part of the western SRP graben (Amini and others, 1984), and in the Smith Prairie area (Howard and others, 1982; Vetter and Shervais, 1992). The range of ages in figure 8 also indicates that this Late Pliocene and Pleistocene interval of volcanism started about 2.2 Ma ago and continued up to within 0.1 Ma of the present. These basalts were erupted following a non-volcanic hiatus in

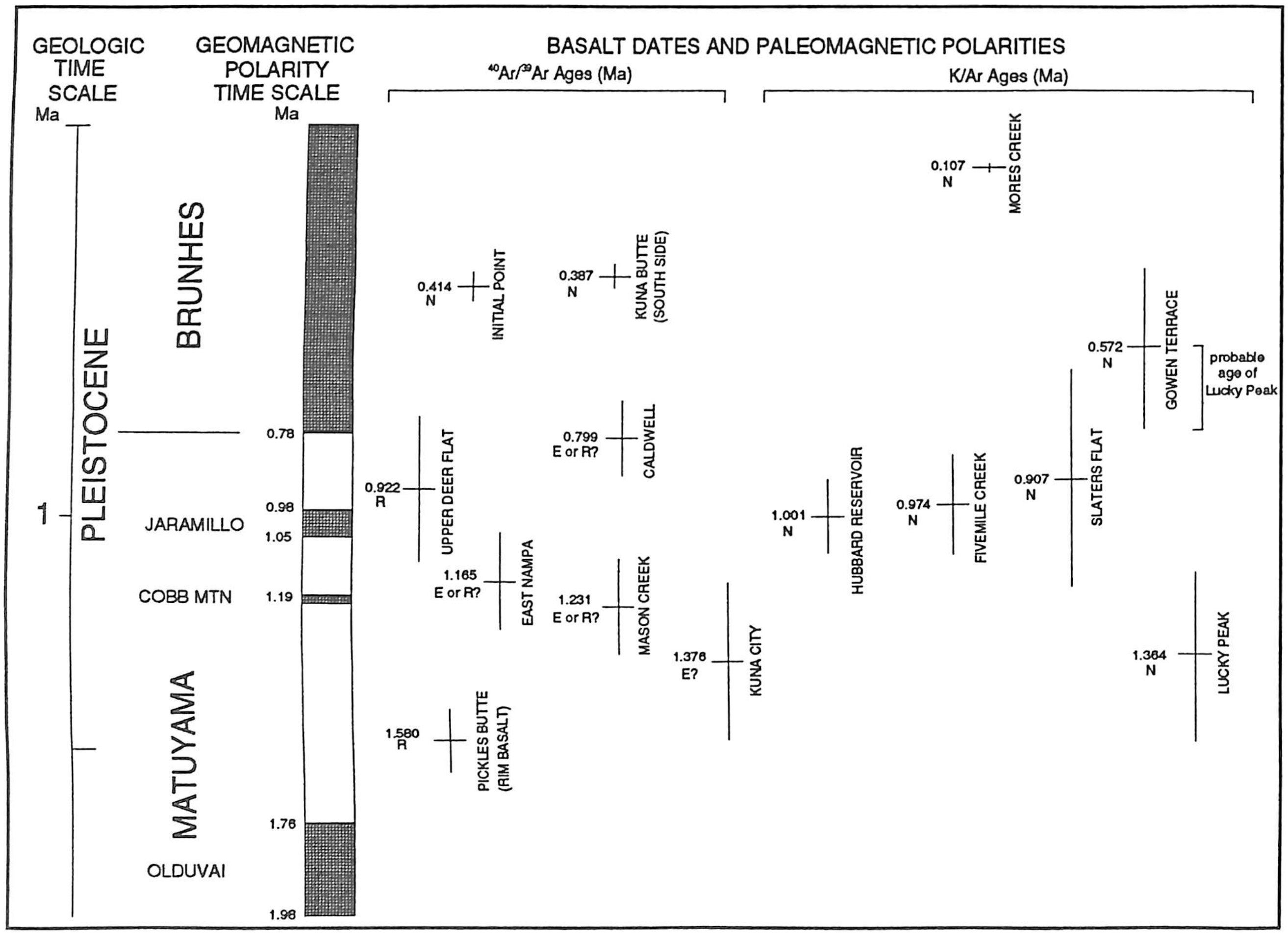

FIGURE 7. Results of dating of basalts in the Boise Valley and adjoining area. $^{40}Ar/^{39}Ar$ and K/Ar ages grouped separately. Magnetic polarities of each basalt shown by N or R. Time scales shown for reference. Geomagnetic time scale adapted from Mankinen and Dalrymple (1979) as modified by Shackleton and others (1990) and Cande and Kent (1992). Length of vertical age bar shows the precision limit of each date.

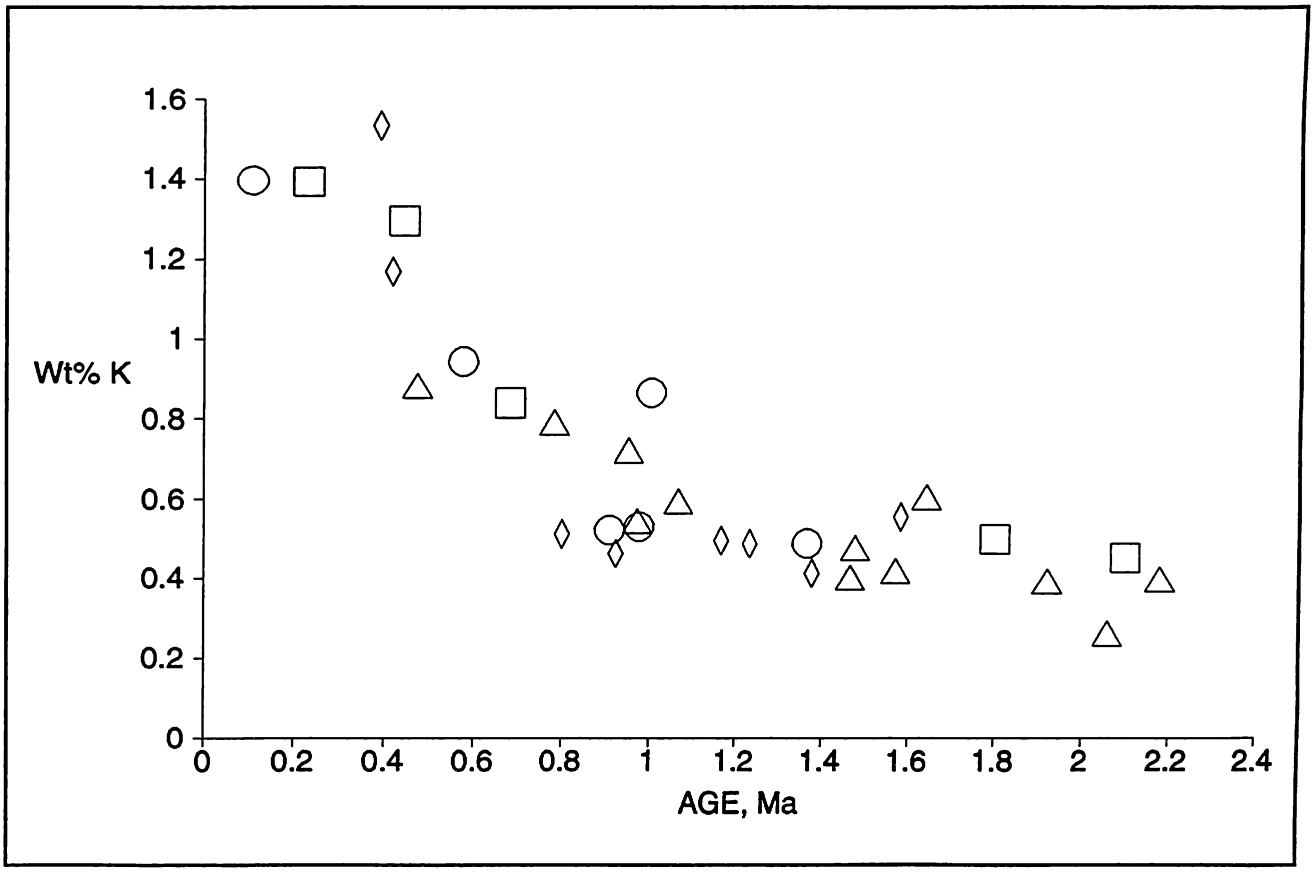

FIGURE 8. Percent potassium plotted against age of dated basalts. Chemical data from the following sources: *circles*, potassium values and K/Ar dates in table 1; *diamonds*, unpublished potassium analyses by Bill Bonnichsen and $^{40}Ar/^{39}Ar$ in table 2; *squares*, potassium values and K/Ar dates reported by Howard and others (1982); *triangles*, potassium values and K/Ar dates reported by Amini and others (1984).

the western SRP that lasted for a few million years. The next oldest dated western SRP basalt is the 7.16 Ma age reported for the basalt of Fossil Butte (Amini and others, 1984).

BASALT COMPOSITIONAL VARIATION IN THE WESTERN SRP GRABEN

The abundances of TiO_2 and K_2O versus Mg/(Mg+Fe) for all the dated samples shown in figure 8, for which major element analyses are available (table 4, this report; Vetter and Shervais, 1992; and Bonnichsen, unpublished data), are plotted in figure 9. In the TiO_2 versus Mg/(Mg+Fe) plot a generally continuous trend of increasing TiO_2 with decreasing Mg/(Mg+Fe) can be seen, whereas there is much more scatter in the K_2O versus Mg/(Mg+Fe) plot. Howard and Shervais (1973) and Howard and others (1982) noted that, in the Smith Prairie area, several of the basalt units with high K_2O abundances contain granitic inclusions. Vetter and Shervais (1992) suggested that two types of basalt may have erupted in the Smith Prairie area: (1) an older group of silica-saturated olivine tholeiites characterized by low alkalis and low Mg/(Mg+Fe) ratios, and (2) a younger group of basalts that have higher alkalis and higher Mg/(Mg+Fe) ratios and are transitional between olivine tholeiites and alkali olivine basalts. Vetter and Shervais note that the chemical compositions of some of the Smith Prairie basalts show evidence of the assimilation of crustal material, but they further suggested that some of the youngest basalts may have originated from a different, more alkalic, mantle source than did the earlier olivine tholeiites.

We have found that, for many of the youngest basalts from throughout the western SRP area, the ones with elevated K_2O contents also have elevated contents of Na_2O and SiO_2. However, these same rocks show neither relatively high nor low Mg/(Mg+Fe) ratios or TiO_2 contents, as related to the abundances of alkalis (Bonnichsen, unpublished chemical analyses). This observation, coupled with the generally inhomogeneous abundances of K_2O in many units, would argue that assimilation of granitic material was an important cause of the late-stage alkali enrichment. In general, we agree with Vetter and Shervais (1992) that both assimilation and different basalt sources may have contributed to the chemical variability of the basalts erupted in the western SRP graben and in the Smith Prairie area. Which cause is really the more important for the basalts becoming more alkalic in the latter stages of the 2.1 million year old volcanic cycle, as portrayed in figure 8, is not yet clear.

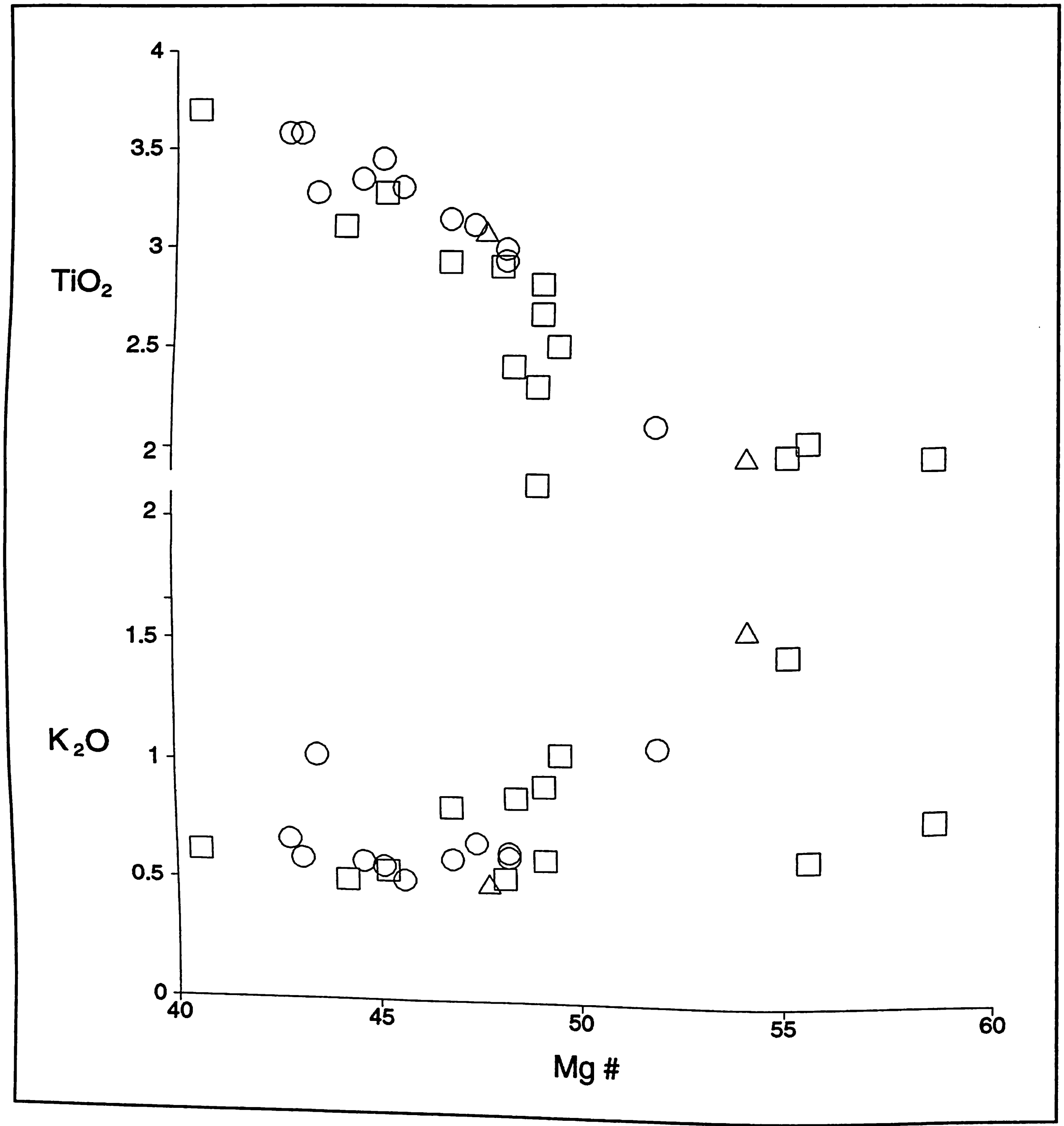

FIGURE 9. TiO_2 and K_2O plotted against Mg # for the dated basalts. Chemical data from the following sources: *circles*, table 4; *squares*, unpublished analyses by Bill Bonnichsen; *triangles*, Vetter and Shervais (1992).

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