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NEW K-Ar AGES OF MAFIC LAVAS FROM THE BASIN AND RANGE–CASCADE TRANSITION ZONE IN NORTHEASTERN CALIFORNIA AND SOUTHERN OREGON

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The distribution of major volcanic rock types in the Pacific Northwest is in part attributed to tectonic interactions between the subducting Juan de Fuca plate and the overriding western portion of the North American plate (Atwater, 1970). During the past five million years, subduction directly or indirectly accounts for the origin of the predominantly calc-alkaline extrusive rocks of the Cascade arc (Thorpe, 1982). Likewise, during at least the past five million years, the tensile stresses involved with the development of the Basin and Range gave rise to faulting and basaltic volcanism (Lawrence, 1976; Hart and others, 1984). One of the objectives of this study was to evaluate the age and distribution of volcanic materials within the northwestern Basin and Range—Cascade arc transitional area.

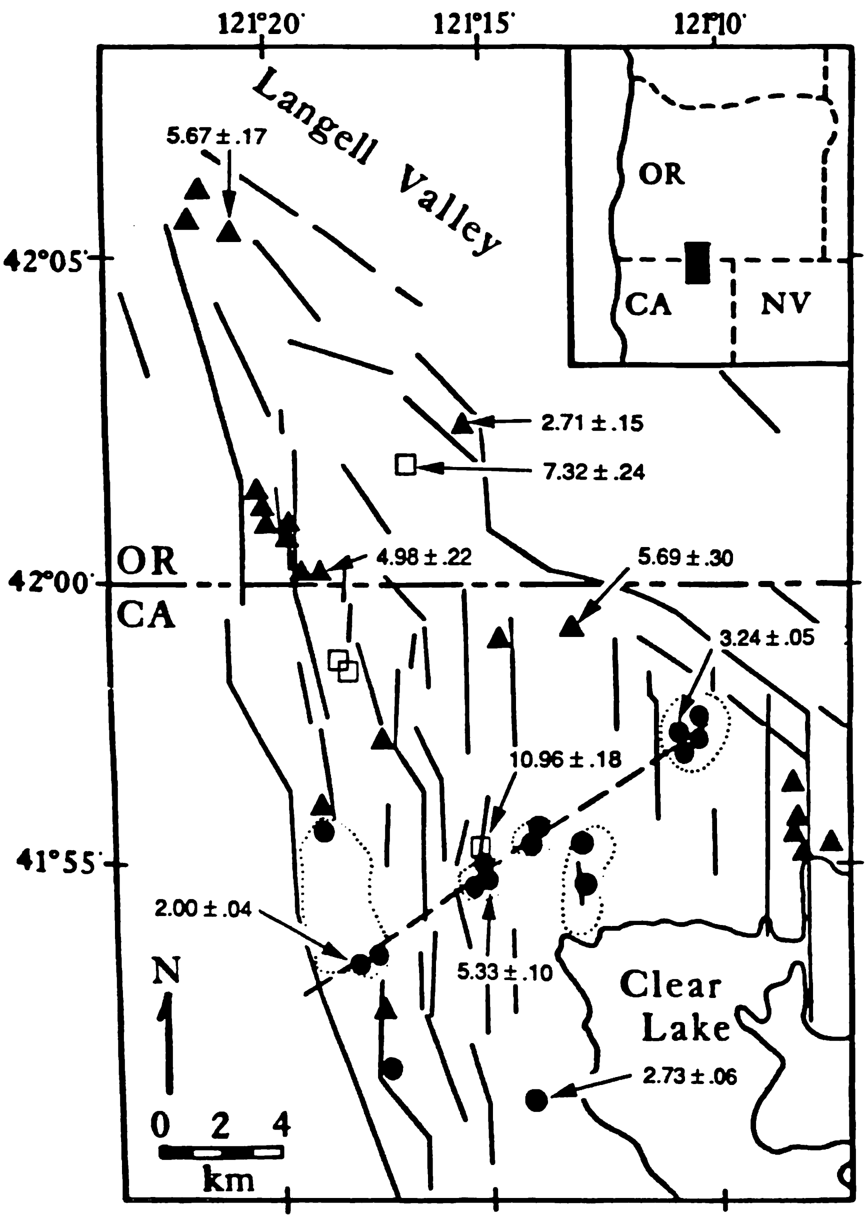

FIGURE 1. Map of study area showing distribution of major rock types, faults, and locations of dated samples. Samples are labelled according to their age (Ma) and correspond to the samples shown in table 1 and the sample descriptions. Filled circles are CABA lavas, filled triangles are HAOT lavas, and open squares are older lavas of the chemically heterogeneous group. Faults are marked as bold black lines. Areas enclosed by dots represent concentrations of CABA vents and/or associated flows. CA = California; NV = Nevada; OR = Oregon. *Note:* Sample KM86-34 is not located on this map.

The volcanic rocks found northeast of the Medicine Lake Highland and in the western portion of the Devil's Garden Lava field (McKee and others, 1983) help to define a portion of the northwestern Basin and Range–Cascade arc transitional area. The study area (fig. 1) is located within the little characterized west-central portion of the Devil's Garden lava field. This area is also impinged by the northeastern extent of a proposed segment boundary of the Cascade volcanic arc (Hughes and others, 1980).

Petrographic and geochemical data indicate that two main rock types characterize the study area; [1] calc-alkaline basalts/basaltic andesites (CABA), and [2] low-K, high alumina olivine tholeiites (HAOT). A third, less abundant suite of basalts and basaltic andesites is also observed. In some cases these lavas display chemical characteristics intermediate between those of CABA and HAOT (e.g. KM87-53), and in other cases they are very similar to the CABA except for markedly higher Sr contents (e.g. compare KM86-96 to a typical CABA, KM86-78). Chemical analyses for these three types are given in table 1 and their sampled distributions are shown on figure 1.

The CABA from this area erupted from small cinder cones aligned parallel to the direction of plate convergence (N50°E; Atwater, 1970). These cinder cones are similar in size and orientation to those documented by Hughes and Mertzman (1976) and Hart and others (1979) in areas adjacent to the Medicine Lake Highland. Rocks of the second major type (HAOT) are indistinguishable from those described by Hart and others (1984) and Bullen (1986). All HAOT lavas are found cut by or filling the valleys formed by north-south and northwest trending faulting. This faulting is typical of the northern termination of east-west extension in the northwestern Basin and Range (Lawrence, 1976). Lavas of the third group have field affinities more similar to HAOT, but are also observed in close spatial association to some CABA lavas.

TABLE 1. Major and trace element data and normative mineralogy.

Sample Type	86–34 Other	85–51 HAOT	86–56 HAOT	86–72 HAOT	86–78 CABA	86–80 CABA	86–96 Other	87–11 CABA	87–50 CABA	87–53 Other	87–128 HAOT
SiO_2	50.84	47.66	47.49	46.73	55.51	55.12	54.14	57.03	50.99	50.92	47.94
TiO_2	0.99	1.47	0.86	0.77	0.88	1.21	1.00	1.68	1.24	1.26	0.93
Al_2O_3	17.49	17.13	17.50	16.79	17.28	17.16	17.36	16.37	17.98	18.33	16.80
Fe_2O_3	3.71	3.53	4.25	1.81	3.98	3.47	2.90	9.92	10.01	10.61	10.34
FeO	5.14	8.16	5.86	8.29	3.75	4.93	5.20	—	—	—	—
MnO	0.15	0.19	0.18	0.18	0.13	0.14	0.14	0.18	0.16	0.16	0.17
MgO	6.72	7.21	8.90	9.67	4.80	3.68	4.23	2.68	6.46	6.34	9.04
CaO	9.17	9.99	11.34	11.82	6.99	7.30	6.97	6.45	9.47	9.27	11.80
Na_2O	3.54	3.33	2.64	2.44	4.07	4.27	4.10	4.30	3.54	3.61	2.46
K_2O	0.73	0.38	0.20	0.23	1.30	1.38	2.22	1.39	0.55	0.58	0.19
P_2O_5	0.26	0.30	0.11	0.09	0.22	0.33	0.48	0.73	0.43	0.39	0.20
L.O.I.	0.83	0.58	0.86	0.59	0.59	0.68	0.96	0.25	−0.05	−0.02	−0.39
TOTAL	99.57	99.93	100.19	99.41	99.50	99.67	99.70	100.97	100.78	101.45	99.48
qtz	0.00	0.00	0.00	0.00	4.22	4.18	0.78	9.46	0.00	0.00	0.00
or	4.31	2.25	1.18	1.36	7.68	8.16	13.12	8.21	3.25	3.43	1.12
ab	29.95	28.18	22.34	18.55	34.44	36.13	34.69	36.39	29.95	30.55	20.82
an	29.68	30.67	35.31	34.18	25.04	23.58	22.41	21.26	31.55	32.10	34.24
ne	0.00	0.00	0.00	1.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
di	11.42	13.79	16.37	19.36	6.65	8.57	7.37	4.92	10.22	9.22	18.55
hy	11.67	0.75	1.66	0.00	15.08	11.31	13.69	10.32	14.30	12.46	6.07
ol	5.49	15.70	16.97	19.94	0.00	0.00	0.00	0.00	3.50	5.64	12.52
mt	3.61	4.31	3.42	2.62	3.45	3.93	3.62	4.61	3.97	4.00	3.52
il	1.88	2.79	1.63	1.46	1.67	2.30	1.90	3.19	2.36	2.39	1.77
ap	0.60	0.70	0.25	0.21	0.51	0.76	1.11	1.69	1.00	0.90	0.46
Rb	6	< 5	5	5	21	34	21	18	10	< 5	5
Sr	711	446	321	336	503	578	709	453	579	595	336
Ba	339	283	129	155	405	464	768	567	307	379	204
Y	13	41	30	23	20	24	16	64	22	23	27
Zr	99	113	86	47	161	177	172	160	94	96	44
V	196	235	237	241	164	225	161	175	246	269	278
Ni	107	142	191	175	75	37	49	< 10	53	97	129
Cr	181	137	210	224	113	71	65	< 10	48	68	241

Notes: All samples have KM-prefix; major elements in wt.%; trace elements in ppm; L.O.I. = loss on ignition.

RESULTS

We report 11 new whole rock K-Ar ages on representative samples from the previously defined rock types (fig. 1, table 1, sample description summary). The analyzed lavas range in age from 2.0 to 11.0 Ma, in agreement with the range reported on chemically similar lavas from this general region (McKee and others, 1983; Hart and others, 1984; Pickthorn and Sherrod, 1990). These results indicate that within the study area the CABA are between 2.0 and 5.3 Ma in age and the HAOT are between 2.7 and 5.7 Ma in age. Older ages ranging from 6.2 to 11.0 Ma characterize the third, chemically heterogeneous group of lavas.

The data clearly show (fig. 1) that the two major rock types, CABA and HAOT, were erupting contemporaneously. In addition, the age range defined by lavas from vents along the N50°E CABA trend (fig. 1) is consistent with estimates of the timing of correspondingly oriented convergence between the Juan de Fuca and North American plates (Atwater, 1970). The close spatial and temporal association of distinct rock types (CABA and HAOT) and their associated distinct structural styles indicate that magma generation and evolution within the transition zone between the Basin and Range and Cascade provinces has been a complex process that is strongly linked to the interfingering structural and tectonic styles. Petrologic details of these relationships, and the significance of the older ages observed for the third, more chemically diverse suite will be discussed elsewhere.

Argon measurement procedures follow those described by Hart and Carlson (1985) and Hart and others (1984).

TABLE 2. Potassium values for K-Ar geochronology.

Sample	(A)	(B)	(C)	(D)	(E)
KM86-34	0.730	0.742	—	—	0.742
KM86-51	0.380	0.386	—	—	0.386
KM86-56	0.200	0.192	0.214	0.201	0.208
KM86-72	0.230	0.200	—	—	0.200
KM86-78	1.300	—	1.279	1.256	1.267
KM86-80	1.380	1.379	1.368	1.375	1.374
KM86-96	2.220	2.282	—	—	2.282
KM87-11	1.390	—	1.463	1.361	1.412
KM87-50	0.550	—	0.634	0.621	0.627
KM87-53	0.580	—	0.635	0.621	0.628
KM87-128	0.190	—	0.243	0.231	0.237

A —Major element analysis (KM86-X, XRF; KM87-X, DCP): whole rock powders
B —Flame photometry: powdered from 12–35 mesh Ar split
C —DCP (dissolution 1): powdered from 12–35 mesh Ar split
D —DCP (dissolution 2): powdered from 12–35 mesh Ar split
E —K_2O concentrations used in age calculations; using either (B), average of (B)(C)(D), or average of (C)(D)

Note: All values in wt.% K_2O

Potassium concentrations were determined by XRF, Flame Photometer, and/or Direct Current Argon Plasma Spectrometer (DCP). Comparisons of the results of these different methods are given in table 2. All samples were analyzed petrographically to assure minimal secondary alteration. Reproducibility of the Ar measurement techniques was tested by analyzing one sample in duplicate (KM86-56). Therefore, the age used on figure 1 is the calculated average age of 2.71 ± 0.15 Ma. The decay constants used in the age calculations are: $\lambda_\epsilon = 5.81 \times 10^{-11}$ yr^{-1}; $\lambda = 5.543 \times 10^{-11}$ yr^{-1}; and $^{40}K/K = 1.167 \times 10^{-4}$ atom/atom.

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SAMPLE DESCRIPTIONS

1. *KM86-34* K-Ar

Basalt (42°15'15", 121°01'00"; NE/4,S22, T38S,R14E; top flow at summit of Horsefly Mtn., Klamath Co., OR). Fine grained, holocrystalline, slightly trachytic; olivine phenocrysts; plagioclase is predominantly labradorite (An_{56-58}). MODE: 46.1% plagioclase, 26.4% olivine, 16.7% augite, 5.7% oxide, 5.1% matrix. *Analytical data:* Sample weight = 7.0433 gm; K_2O = 0.742 (wt)%; $^{40}Ar^*$ = 6.5992 × 10^{-12} mol/gm; $^{40}Ar^*$ = 32.90%. *Note:* This sample is not found on figure 1.

(whole rock) 6.17 ± 0.13 Ma

2. *KM86-51* K-Ar

Basalt (42°05'45l", 121°20'45"; SW/4,S18, T40S,R12E; top flow at S end of Harpold Reservoir, Klamath Co., OR). Fine to medium grained, diktytaxitic, holocrystalline, intergranular to subophitic; some iddingsitized olivine; plagioclase is predominantly labradorite (An_{58-60}). MODE: 48.2% plagioclase, 25.4% olivine, 21.0% augite, 3.9% oxide, 1.5% matrix. *Analytical data:* Sample weight = 8.0790 gm; K_2O = 0.386 (wt)%; $^{40}Ar^*$ = 3.1534 × 10^{-12} mol/gm; $^{40}Ar^*$ = 38.66%.

(whole rock) 5.67 ± 0.17 Ma

3. *KM86-56* K-Ar

Basalt (42°02'15", 121°15'15"; SE/4,S2, T41S,R12E; first exposed flow up from West Langell Valley Road, Klamath Co., OR). Medium grained, diktytaxitic, holocrystalline, intergranular to subophitic; some iddingsitized olivine; plagioclase is predominantly labradorite (An_{57-59}). MODE: 51.3% plagioclase, 21.8% olivine, 23.1% augite, 2.5% oxide, 1.3% matrix. *Analytical data:* Sample weights = 8.1033 gm, 7.9360 gm; K_2O = 0.208 (wt)%, 0.208 (wt)%; $^{40}Ar^*$ = 7.6665 × 10^{-13} mol/gm, 7.9422 × 10^{-13} mol/gm; $^{40}Ar^*$ = 19.21%, 18.58%. *Note:* Figure 1 shows average age: 2.71 ± 0.15 Ma.

(whole rock) 2.77 ± 0.16 Ma
(whole rock) 2.65 ± 0.13 Ma

4. *KM86-72* K-Ar

Basalt (41°59'00", 121°13'15"; SW/4,S19, T48N,R7E; Hopeless Pass, Modoc Co., CA). Medium grained, diktytaxitic, holocrystalline, intergranular to subophitic; plagioclase is predominantly labradorite (An_{61-64}). MODE: 46.5% plagioclase, 23.4% olivine, 22.8% augite, 5.6% oxide, 1.7% matrix. *Analytical data:* Sample weight = 6.0184 gm; K_2O = 0.200 (wt)%; $^{40}Ar^*$ = 1.6406 × 10^{-12} mol/gm; $^{40}Ar^*$ = 24.73%.

(whole rock) 5.69 ± 0.30 Ma

5. *KM86-78* K-Ar

Basaltic andesite (41°53'30", 121°17'50"; NW/4,S28,T47N,R6E; cliff forming flow on top of Horse Mtn., Modoc Co., CA). Fine to medium grained, holocrystalline; plagioclase laths show distinct sieve texture or resorption; plagioclase is predominantly andesine (An_{49-50}). MODE: 20.9% plagioclase, 0.6% olivine, 1.0% cpx, 5.5% oxide, 72.0% matrix. *Analytical data:* Sample weight = 4.4513 gm; K_2O = 1.267 (wt)%; $^{40}Ar^*$ = 3.6593 × 10^{-12} mol/gm; $^{40}Ar^*$ = 24.47%.

(whole rock) 2.00 ± 0.04 Ma

6. *KM86-80* K-Ar
Basaltic andesite (41°51′00″, 121°13′50″; SE/4,S1,T46N,R6E; top flow at N end of Clear Lake Hills, Modoc Co., CA). Fine grained, holocrystalline, seriate textured; plagioclase shows some resorption texture; minor subhedral olivine phenocrysts; plagioclase is predominantly labradorite (An_{55-57}). MODE: 21.2% plagioclase, 5.4% olivine, 2.0% cpx, 4.0% oxide, 67.4% matrix. *Analytical data:* Sample weight = 6.0886 gm; K_2O = 1.374 (wt)%; $^{40}Ar^*$ = 5.4300 × 10^{-12} mol/gm; $^{40}Ar^*$ = 22.38%.

(whole rock) 2.73 ± 0.06 Ma

7. *KM86-96* K-Ar
Basaltic andesite (42°02′00″, 121°16′30″; NE/4,S10,T415,R12E; top flow at summit of Bryant Mtn., Klamath Co., OR). Medium grained, holocrystalline, vesicular, trachytic; iddingsitized olivine phenocrysts; plagioclase is predominantly andesine (An_{40}). MODE: 59.4% plagioclase, 22.9% olivine, 6.3% cpx, 8.2% oxide, 3.2% matrix. *Analytical data:* Sample weight = 6.0288 gm; K_2O = 2.282 (wt)%; $^{40}Ar^*$ = 2.4097 × 10^{-11} mol/gm; $^{40}Ar^*$ = 41.39%.

(whole rock) 7.32 ± 0.24 Ma

8. *KM87-11* K-Ar
Basaltic andesite (41°57′15″, 121°10′15″; SE/4,S33,T48N,R7E; from Carr Butte, Modoc Co., CA). Fine grained, holocrystalline, seriate textured; sieve or resorption textured plagioclase laths; plagioclase is predominantly andesine (An_{45}). MODE: 9.3% plagioclase, 1.0% olivine, 2.0% cpx, 0.2% opx, 2.5% oxide, 85.0% matrix. *Analytical data:* Sample weight = 4.6760 gm; K_2O = 1.412 (wt)%; $^{40}Ar^*$ = 6.5772 × 10^{-12} mol/gm; $^{40}Ar^*$ = 21.32%.

(whole rock) 3.24 ± 0.05 Ma

9. *KM87-50* K-Ar
Basaltic andesite (41°54′45″121°14′50″′; SE/4,S14,T47N,R6E; from vent, Modoc Co., CA). Fine to medium grained, holocrystalline; subhedral to euhedral phenocrysts of olivine; plagioclase shows some resorption; plagioclase is predominantly andesine (An_{48}). MODE: 49.4% plagioclase, 22.0% olivine, 10.5% cpx, 11.4% oxide, 6.7% matrix. *Analytical data:* Sample weight = 5.0577 gm; K_2O = 0.627 (wt)%; $^{40}Ar^*$ = 4.8151 × 10^{-12} mol/gm; $^{40}Ar^*$ = 37.80%.

(whole rock) 5.33 ± 0.10 Ma

10. *KM87-53* K-Ar
Basalt (41°55′15″, 121°14′55″; NE/4,S14, T47N,R6E; flow directly below KM87-50, Modoc Co., CA). Fine to medium grained, diktytaxitic, holocrystalline, intergranular to subophitic; some iddingsitized olivine; plagioclase is predominantly labradorite (An_{58-60}). MODE: 46.8% plagioclase, 23.5% olivine, 21.1% augite, 6.5% oxide, 2.1% matrix. *Analytical data:* Sample weight = 5.0254 gm; K_2O = 0.628 (wt)%; $^{40}Ar^*$ = 9.9261 × 10^{-12} mol/gm; $^{40}Ar^*$ = 57.76%.

(whole rock) 10.96 ± 0.18 Ma

11. *KM87-128* K-Ar
Basalt (42°00′00″, 121°18′35″; NE/4,S20, T41S,R12E; top flow on E side of valley, Klamath Co., OR). Fine grained, diktytaxitic, holocrystalline, intergranular to subophitic, glomerporphyritic; some iddingsitized olivine; plagioclase is predominantly labradorite (An_{64-66}). MODE: 50.2% plagioclase, 22.7% olivine, 24.8% augite, 1.6% oxide, 0.7% matrix. *Analytical data:* Sample weight = 6.7287 gm; K_2O = 0.237 (wt)%; $^{40}Ar^*$ = 1.6977 × 10^{-12} mol/gm; $^{40}Ar^*$ = 26.68%.

(whole rock) 4.98 ± 0.22 Ma

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