Potassium-Argon Ages for Plutons in the Eastern and Southern Sierra Nevada Batholith, California

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By EDWARD A. du BRAY and DAVID A. DELLINGER

A study of the ages of 26 plutons in the
eastern and southern Sierra Nevada

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Potassium-Argon Ages for Plutons in the Eastern and Southern Sierra Nevada Batholith, California

By Edward A. du Bray *and* David A. Dellinger

Abstract

The ages of biotite and/or hornblende separates from 26 plutons in the eastern and southern Sierra Nevada were determined by the K-Ar method. Both biotite and hornblende age determinations were made for 14 of these samples. Six of the biotite-hornblende pairs give concordant ages; the rest of the biotites give younger ages. Two samples of hornblende give ages considered to be too young, which may be a consequence of post-magmatic potassium metasomatic alteration of hornblende. Most of the dated plutons were emplaced in Late Cretaceous time at the culmination of magmatic activity in the Sierra Nevada. Samples of two plutons not cut by the Independence dike swarm have ages of around 123 Ma; the dike swarm must have been emplaced prior to this time.

INTRODUCTION

Age determinations have been made for many plutons of the Sierra Nevada batholith. Evernden and Kistler (1970) dated plutons in the accessible parts of the range, and ages were determined for plutons in the southern Sierra Nevada by Chen (1977) and Chen and Moore (1979, 1982). Ages for a number of plutons in the central Sierra Nevada were determined by Stern and others (1981). The ages of plutons in the eastern and southern Sierra Nevada, however, are less well known and are the subject of this study.

METHODS

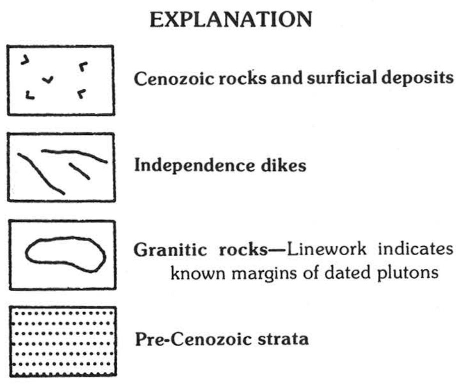
Rock samples of 2–5 kg were collected at locations (fig. 1) as far from contacts as was practical to minimize the effects of argon loss due to reheating during subsequent magmatic events. Samples were crushed and sieved; biotite and hornblende separates, at least 99 percent pure, were made from -60+80 mesh size fraction using standard laboratory techniques based on density, magnetic properties, and shape differences. Aliquots of biotite and hornblende were analyzed by the Analytical Labs of the U.S. Geological Survey in Menlo Park for K_2O by a lithium metaborate flux fusion-flame photometry technique; lithium acts as an internal standard (Ingamells, 1970).

All argon determinations were made in the U.S. Geological Survey's isotope geology laboratory in Menlo Park, California, using standard isotope-dilution techniques described by Dalrymple and Lanphere (1969). Samples of clean argon gas were analyzed using a 60° sector, 15.2 cm-radius, Neir-type mass spectrometer, operated in the static mode. Ages were calculated using the constants of the subcommission on geochronolgy (Steiger and Jager, 1977).

ANALYTICAL PRECISION

Analytical precision (error), which is expressed at the one sigma level, assigned to the determined ages was computed using a modified version of the equation developed by Cox and Dalrymple (1967). In addition to the factors included in their equation (errors in determination of K_2O, of $^{40}Ar/^{38}Ar$ and $^{38}Ar/^{36}Ar$, of ^{38}Ar in the spike, and the percentage of ^{40}Ar in the sample) we have included spectrometer discrimination errors and errors in the measurement of isotopic ratios in the spike. The contributions to total error by these factors are small in most cases but are important components of total error in others. The total error computed by our equation is consistent with the empirically predicted error of Tabor and others (1985).

The largest source of uncertainty in most of the age determinations was in the K_2O analyses (table 1). Several replicate K_2O determinations of split mineral separates were made. Relative standard deviations for replicate analyses of K_2O in biotites (mean, 3.0 percent) ranged from 1.6 to 4.7 percent (not including a chloritized sample with a standard deviation of 7.7 percent) and from 0.5 to 10.3 percent in hornblendes. We believe the



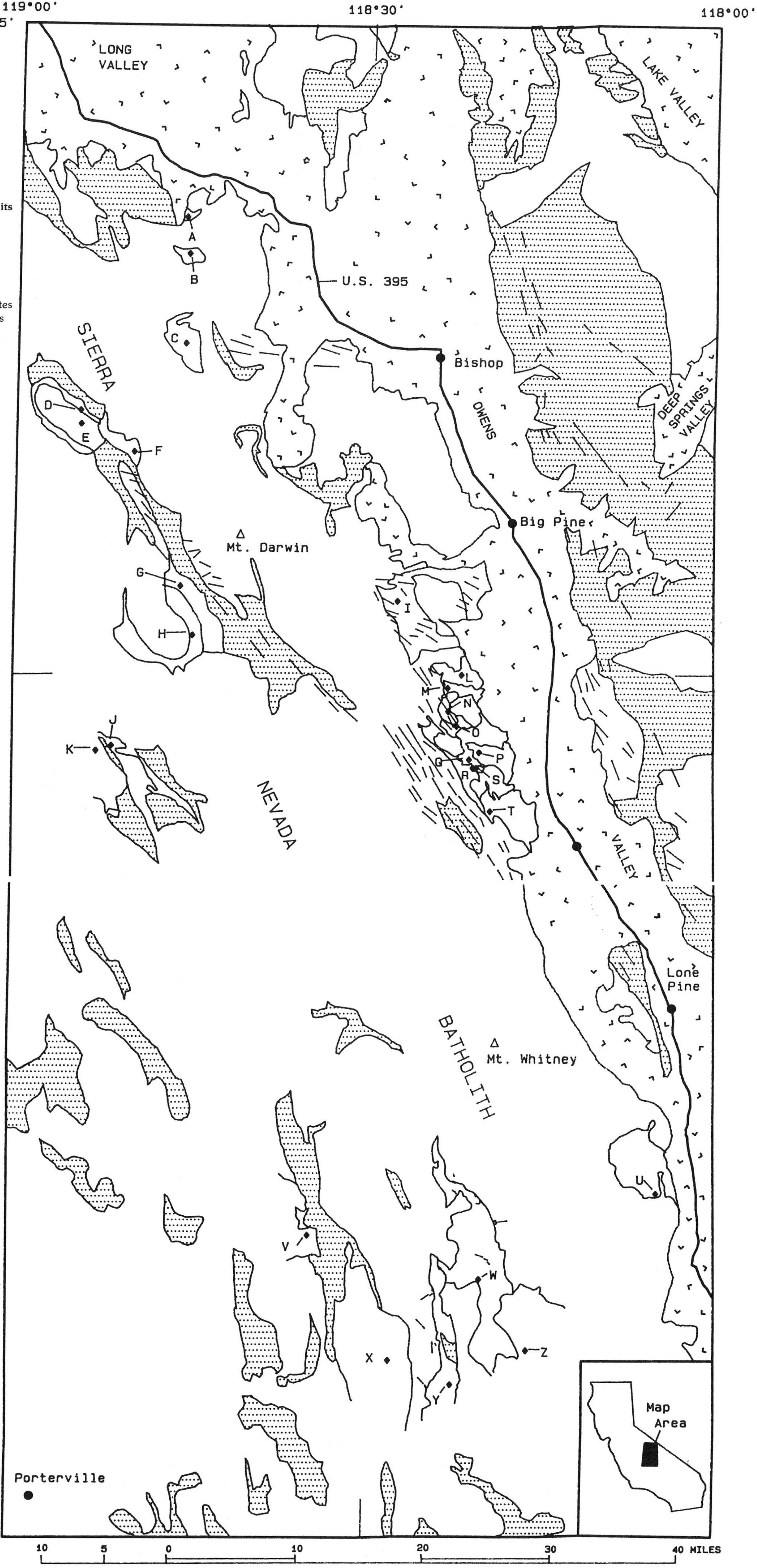


Figure 1. Map showing sample localities and generalized outcrop patterns of the dated plutons and the Independence dike swarm of the eastern and southern Sierra Nevada batholith

Table 1. Analytic data for samples with multiple K_2O analyses

Field no.	Map no.	Mineral	K_2O wt. %	Mean K_2O wt. %	Standard deviation wt. %
8-133	D	biotite	2.31	2.28	0.05
8-133	D	do.	2.24		
8-127	J	do.	9.01	8.79	0.31
8-127	J	do.	8.57		
8-48	P	do.	7.84	7.44	0.57
8-48	P	do.	7.03		
8-47	Q	do.	2.98	2.98	-
8-47	Q	do.	2.98		
8-232	S	hornblende	1.475	1.410	4.72
8-232	S	do.	1.342		
8-232	S	do.	1.412		
8-59	T	biotite	8.89	8.79	1.61
8-59	T	do.	8.69		
9-7	U	hornblende	1.147	1.07	10.25
9-7	U	do.	0.992		
9-77	V	do.	1.271	1.276	0.55
9-77	V	do.	1.281		

10.3 percent error computed for one hornblende to be anomalous with respect to the pooled coefficient of variation determined for the laboratory by many replicate analyses of other samples; the mean error for other hornblende samples is 2.6 percent. These values are larger than those cited by Cox and Dalrymple (1967) and may be due to sample inhomogeneity rather than analytical error; neither cause can be ruled out. Errors of 2 percent (biotite) and 3 percent (hornblende) were assigned to samples for which only a single K_2O determination was made.

GEOLOGY

The Sierra Nevada batholith is a composite intrusive complex composed of hundreds of individual Mesozoic-age plutons; the majority of its constituent plutons are Cretaceous in age (Stern and others, 1981; Chen and Moore, 1982). The batholith intruded older volcanic and sedimentary rocks that have been metamorphosed at greenschist to amphibolite facies conditions. These rocks also account for about 10 percent of the area within the batholith, where they occur as roof pendants. The intrusive rocks of the Sierra Nevada batholith range in composition from hornblende gabbro to alaskitic granite. The granitoid rocks are typically medium grained and homogeneous with respect to texture and composition within a given pluton, although some display well-developed concentric zoning. The granitoids contain quartz, potassium feldspar, plagioclase, biotite, and hornblende as principal constituents; minor constituents include iron-titanium oxides, zircon, apatite, and sphene. The individual characteristics of the 26 dated plutons are presented in table 2, and their geographic distribution is shown in figure 1.

RESULTS AND DISCUSSION

Analytical data for the samples are summarized in table 3.

The K_2O contents of biotite separated from samples Q and D are very low relative to K_2O contents from other plutons of the Sierra Nevada batholith, which range from 8.28 to 9.98 weight percent (Dodge and others, 1969). Petrographic examination of these biotite separates indicates that much of the biotite in these samples is chloritized, yet the separates give geologically reasonable ages. Dalrymple and Lanphere (1969) indicate that chloritized biotites give appropriate ages in many cases, regardless of when chloritization occurred. Presumably, potassium loss during chloritization is accompanied by a matching argon loss. The $^{40}Ar/^{39}Ar$ spectra for recently analyzed chloritzed biotites, however, are wildly discordant (L. W. Snee, written commun., 1986) and imply that care is needed in the interpretation of conventional K-Ar ages for chloritized biotite.

The age of biotite separated from sample Q was determined twice; the determined ages for the two splits fall outside the range predicted for the other separates using our error analysis. This is the only case among our determinations for which replicate analyses did not result in overlapping error bars. The ages calculated for these chloritized biotites, though reasonable, are neither as accurate nor as precise as those determined for other samples.

The K_2O contents of some of the hornblende separates are high compared to those for hornblende from other plutons of the Sierra Nevada batholith, which range from 0.37 to 0.95 weight percent (Dodge and others, 1968). In most cases, contamination of hornblende by small inclusions of biotite is indicated. Contamination of this sort should not adversely affect the precision of the age determinations, provided that the splits used for K_2O analysis and argon extraction contained the same proportion of impure grains. The accuracy of the hornblende age could have been adversely effected if there was significant contamination of the hornblende separate by biotite because of the variable argon retention temperatures for the two minerals.

Ages for biotite-hornblende pairs are considered concordant when the difference between the ages determined for the two minerals is less than the critical value (CV), defined by Dalrymple and Lanphere (1969, p. 120). Using this criterion, 8 of our 14 biotite-hornblende pairs yield discordant ages; the observed discordancy has several possible explanations. The argon retention temperature for biotite is 280° ± 40°C (Harrison and

Table 2. Petrographic data for the dated plutons
[--, leaders indicate no data available]

Map no.	Pluton	Average mode: Quartz	K-spar	Plagi-oclase	Color index	Specific gravity	Texture[1]	Grain size[2]	Reference
A	Quartz monzonite of Hilton Creek	31.5	33.8	32.5	2.5	--	A, F	x	Rninehart and Ross (1964).
B	Nonporphyritic phase of the quartz monzonite of Mono Recesses	25.7	30.0	39.6	4.7	2.63	A, B		Lockwood and Lydon (1975).
C	Granodiorite of Chickenfoot Lake	21.3	25.0	39.4	14.4	2.70	A, C, G	y	Lockwood and Lydon (1975).
D	Fine grained facies of quartz monzonite of Bear Dome	24.6	36.2	36.6	2.6	2.62	F	x	Do.
E	Quartz monzonite of Bear Dome	22.6	24.8	43.8	7.9	2.67	F, G	y	Lockwood and Lydon (1975).
F	Quartz monzonite of Turret Peak	25.1	17.8	48.8	8.3	2.70	A, C	y	Do.
G	Granodiorite of Mount Reinstein	21.5	11.6	48.3	18.6	2.71	A, B, I	y	Bateman (1965b).
H	Quartz monzonite of Finger Peak	31.6	27.8	36.5	4.1	2.63	A, B	y	Do.
I	Tinemaha Granodiorite	21.3	23.6	39.0	16.1	2.72	A, C, I	y	Bateman (1965a).
J	Granodiorite of Tombstone Creek	21.6	11.4	48.4	18.6	2.74	A, E, I	y	Do.
K	Quartz monzonite of Brush Canyon	32.2	25.3	36.3	6.2	2.64	A, B	y	Moore and Marks (1972).
L	Taboose pluton	30.9	38.4	28.5	2.1	2.60	A, B	y	Do.
M	Goodale pluton	21.9	32.1	34.2	11.8	2.65	A, B	y	Moore (1963).
N	Siberian pluton	29.5	29.6	36.3	4.6	2.60	A, B	y	Do.
O	Mule Lake pluton--north mass	--	--	--	--	--	A, C, G	y	Do.
P	Spook pluton--light facies	24.4	19.3	47.9	8.4	2.62	A, C	y	Do.
Q	Spook pluton--dark facies	24.5	18.3	46.7	10.6	2.66	A, C	y	Do.
R	Mc Doogle pluton	12.4	17.5	46.6	23.6	2.74	A, B	y	Do.
S	Mule Lake pluton--south mass	--	--	--	--	--	A, C, G	y	Do.
T	McGann pluton	17.2	35.5	35.9	11.5	2.64	A, B	y	Do.
U	Granite of Carroll Creek	24.5	31.9	36.6	7.1	2.63	A, B	z	du Bray and Dellinger (1981).
V	Granodiorite of Quinn Peak	23.5	12.2	50.1	14.2	2.72	A, E	y	Do.
W	Granite of Window Cliffs	19.7	22.6	46.4	11.3	2.68	A, C, G	y	Do.
X	Granite of White Mountain	24.9	24.9	43.2	5.4	2.62	A, D	y-z	Do.
Y	Granodiorite of Doe Meadow	15.7	10.7	52.0	21.6	2.75	A, B, H	y	Do.
Z	Granodiorite of Redrock Meadow	18.8	20.1	50.5	10.6	2.67	A, C	y	Do.

[1]Texture codes: A. Hypidiomorphic granular.
B. Equigranular.
C. Moderately porphyritic with respect to K-feldspar.
D. Strongly porphyritic with respect to K-feldspar/megacryst bearing.
E. Porphyritic with respect to plagioclase or hornblende.
F. Aplitic.
G. Sheared.
H. Lineated.
I. Strongly foliated.

[2]Grain size codes: x. Fine grained (<1 mm).
y. Medium grained (1 to 5 mm).
z. Coarse grained (>5 mm).

McDougall, 1980; Snee, 1982) and 525° ± 25°C for hornblende (Harrison, 1981). Both of these temperatures are significantly lower than granitoid magma solidus temperatures (Tuttle and Bowen, 1958), which implies that magma solidification occurs well before the onset of argon retention and that ages determined for slowly cooled plutons by the K-Ar method will be younger than true crystallization ages. In particular, biotite gives ages that in many instances are much too young because radiogenic argon does not begin to accumulate until the cooling pluton attains a very low temperature. It is also well established that the diffusion rate of argon from biotite exceeds that for hornblende (Hart, 1964; Hanson and Gast, 1967) and the difference leads to differential argon retention. The hornblende age of discordant biotite-hornblende pairs is considered a minimum age since the radiometric clock in both minerals can be at least partially reset during reheating.

Table 3. K-Ar ages of and analytical data for intrusive rocks, eastern and southern Sierra Nevada batholith, California

Map no.	Field no.	N. lat. deg	N. lat. min	N. lat. sec	W. long. deg	W. long. min	W. long. sec	Mineral	Experiment no.	Age, Ma[1]	%^{40}Ar	$^{40}Ar_{rad}$ ($\times 10^{-11}$ mol/g)	K_2O wt. %	Estimated age, Ma[2]	C/D[3]
A	8-10	37	31	40	118	45	30	biotite	9I221	83.7±1.9	90.54	104.774	8.50		
B	8-4	37	28	54	118	45	23	biotite	9I365	79.7±2.1	88.06	79.7209	6.80		
C	8-21	37	23	03	118	45	32	biotite	0I116	81.4±1.8	82.52	81.7138	6.82	79.8±2.3	
C	8-21	37	23	03	118	45	32	biotite	0I133	78.2±1.8	71.74	72.468	6.82		
C	8-21	37	23	03	118	45	32	hornblende	9I139	88.9±2.9	73.77	27.7326	2.114		D
D	8-133	37	18	08	118	53	46	biotite	9I379	82.1±2.1	72.44	27.5220	2.28		
E	8-132	37	17	19	118	54	16	biotite	9I366	81.7±1.8	89.01	103.315	8.59		
F	8-138	37	15	06	118	49	33	biotite	0I213	76.5±1.9	48.52	81.1123	7.21	76.3±1.7	
F	8-138	37	15	06	118	49	33	biotite	0I329	76.0±1.8	54.84	80.5507	7.21		
F	8-138	37	15	06	118	49	33	biotite	0I427	76.3±1.8	56.77	80.9223	7.21		
F	8-138	37	15	06	118	49	33	hornblende	9I114	81.6±2.2	50.57	9.78249	0.814		D
G	8-109	37	06	04	118	45	45	biotite	0I118	81.8±1.9	77.84	111.527	9.26	80.9±1.0	
G	8-109	37	06	04	118	45	45	biotite	0I623	80.0±1.8	84.34	109.103	9.26		
G	8-109	37	06	04	118	45	45	biotite	0I644	80.8±1.8	84.47	110.145	9.26		
G	8-109	37	06	04	118	45	45	hornblende	9I128	92.7±3.1	59.24	12.0796	0.882	95.1±3.3	
G	8-109	37	06	04	118	45	45	hornblende	0I685	97.4±3.1	60.83	12.7009	0.882		D
H	8-110	37	02	36	118	44	37	biotite	9I177	83.4±1.8	92.59	98.6526	8.03	82.6±1.1	
H	8-110	37	02	36	118	44	37	biotite	9I657	81.8±1.8	69.94	96.7111	8.03		
I	8-28	37	05	01	118	27	03	biotite	0I211	69.5±1.7	58.25	75.0628	7.36	69.2±1.4	
I	8-28	37	05	01	118	27	03	biotite	0I619	68.9±1.6	55.31	74.3693	7.36		
I	8-28	37	05	01	118	27	03	hornblende	9I130	126.9±4.3	58.91	14.5776	0.784	125.7±3.3	
I	8-28	37	05	01	118	27	03	hornblende	9I372	124.4±4.6	43.33	14.2738	0.784		D
J	8-127	36	54	45	118	51	45	biotite	9I612	83.4±3.1	85.17	108.037	8.79	82.7±2.4	
J	8-127	36	54	45	118	51	45	biotite	0I332	82.0±3.0	72.34	106.105	8.79		
J	8-127	36	54	45	118	51	45	hornblende	9I526	84.0±3.5	28.00	13.0270	1.053		C
K	8-125b	36	54	33	118	52	25	biotite	9I210	85.7±1.9	86.78	115.413	9.14		
L	8-42	36	59	53	118	21	45	biotite	9I220	83.1±2.0	79.41	77.5005	6.33		
M	8-40	36	59	11	118	22	56	biotite	9I453	87.9±2.0	86.91	96.6100	7.45		
M	8-40	36	59	11	118	22	56	hornblende	9I371	78.8±8.3	9.43	12.2955	1.06		C
N	8-224	36	54	45	118	22	45	biotite	9I223	77.6±2.1	92.03	95.3255	8.35		
O	8-49	36	56	11	118	21	45	biotite	9I375	77.2±1.7	87.63	90.9322	8.01		
P	8-48	36	54	33	118	20	27	biotite	0I624	72.5±5.4	68.89	79.1234	7.44		

Q	8-47	36	53	52	118	21	22	biotite	9I454	77.1±2.0	65.33	33.8737	2.98	80.5±4.8	
Q	8-47	36	53	52	118	21	22	biotite	0I660	83.0±1.9	72.95	36.8424	2.98		
Q	8-47	36	53	52	118	21	22	hornblende	9I373	75.4±2.7	46.76	8.50243	0.767		C
R	8-231	36	53	19	118	20	44	biotite	9I162	80.9±1.8	87.59	106.951	8.98	80.0±1.3	
R	8-231	36	53	19	118	20	44	biotite	0I642	79.0±1.8	70.01	104.426	8.98		
R	8-231	36	53	19	118	20	44	hornblende	9I374	86.0±4.9	18.25	37.8118	2.98		C
S	8-232	36	53	28	118	20	28	biotite	9I457	79.8±1.8	81.47	76.7070	6.53		
S	8-232	36	53	28	118	20	28	hornblende	9I378	85.7±4.3	49.63	17.8254	1.410		C
T	8-59	36	50	36	118	19	13	biotite	0I100	73.5±1.4	68.46	94.8866	8.79	73.0±0.9	
T	8-59	36	50	36	118	19	13	biotite	0I429	72.5±1.4	66.64	93.5436	8.79		
T	8-59	36	50	36	118	19	13	hornblende	9I140	121.9±0.8	97.24	35.4797	1.954		D
U	9-7	36	23	28	118	04	33	biotite	0I068	78.4±1.9	80.99	89.6996	7.78	77.0±2.0	
U	9-7	36	23	28	118	04	33	biotite	0I330	75.6±2.1	34.87	86.4779	7.78		
U	9-7	36	23	28	118	04	33	hornblende	0I067	94.5±9.8	80.12	14.9289	1.070		C
V	9-77	36	21	17	118	34	23	biotite	0I120	89.7±2.0	82.00	100.656	7.60	89.1±1.5	
V	9-77	36	21	17	118	34	23	biotite	0I643	88.5±1.9	78.84	99.2515	7.60		
V	9-77	36	21	17	118	34	23	hornblende	9I523	94.0±2.5	33.73	17.7164	1.276	95.1±1.6	
V	9-77	36	21	17	118	34	23	hornblende	0I620	96.2±1.8	65.85	18.1456	1.276		D
W	9-17	36	17	27	118	20	03	biotite	0I069	75.3±1.8	59.01	78.0221	7.05		
W	9-17	36	17	27	118	20	03	hornblende	9I609	102.1±3.6	46.24	23.6360	1.555	104.3±2.4	
W	9-17	36	17	27	118	20	03	hornblende	0I331	106.0±3.6	45.82	24.4388	1.555		D
X	9-31	36	12	21	118	27	29	biotite	0I098	80.3±1.8	73.71	96.9623	8.20	80.5±1.6	
X	9-31	36	12	21	118	27	29	biotite	0I335	80.7±1.8	79.70	97.4634	8.20		
Y	9-38	36	10	34	118	22	15	biotite	9I611	85.1±1.9	80.40	96.7451	7.71		
Y	9-38	36	10	34	118	22	15	hornblende	9I599	125.8±4.0	66.37	19.4715	1.038	122.6±4.5	
Y	9-38	36	10	34	118	22	15	hornblende	0I659	119.4±3.8	67.61	18.438	1.038		D
Z	9-69	36	12	49	118	15	51	biotite	0I212	81.1±1.7	87.06	108.853	9.12	81.3±1.5	
Z	9-69	36	12	49	118	15	51	biotite	0I334	80.3±1.8	75.45	107.769	9.12		
Z	9-69	36	12	49	118	15	51	biotite	0I686	83.9±3.5	74.31	85.8294	9.12		

[1] Uncertainty on ages is one sigma.
[2] Best estimate of pluton ages based on multiple determinations and overlapping error.
[3] Concordant (C) or discordant (D) biotite-hornblende pair; as determined using the critical value (C.V.) of Dalrymple and Lanphere (1969).

Chen and Moore (1979) determined that the Independence dike swarm was emplaced between 149 and 103 Ma. The oldest pluton that they dated that is not cut by the dikes crystallized about 103 Ma. Hornblende ages for the McGann pluton (sample T) and granodiorite of Doe Meadow (sample Y) are 122 Ma and 123 Ma, respectively, and because neither of these plutons is cut by the dikes the age determinations for these plutons further restrict the emplacement time for the Independence dike swarm to between 123 and 149 Ma. The ages of these plutons indicate magmatism in the southern Sierra Nevada at a time coincident with the onset of Cretaceous magmatic activity elsewhere in the range (Evernden and Kistler, 1970; Chen, 1977; Chen and Moore, 1979, 1982; Stern and others, 1981).

Samples O and S were dated to test Moore's (1963) correlation of two isolated masses of the Mule Lake pluton. Both masses are small and surrounded by younger plutons. Ages for sample S biotite-hornblende pair are concordant and imply crystallization between 80 and 86 Ma; the age determined for biotite from sample O is about 77 Ma. Both masses are cut by numerous Independence dikes, however, which indicates that the radiometric ages are too young. The Mule Lake pluton probably crystallized between 149 and 123 Ma ago and was subsequently reheated about 80 Ma, which caused diffusive loss of previously accumulated argon from both biotite and hornblende. Simultaneous potassium metasomatism may have doubled the K_2O content of sample S hornblende, yielding a value twice that characteristic of Sierra Nevada hornblende (Dodge and others, 1968). Our K-Ar determinations provide no definitive information concerning the correlation or intrusive age of the two intrusives that form the Mule Lake pluton.

A determination on hornblende from sample W, which was collected from the sheared and altered granite of Window Cliffs (du Bray and Dellinger, 1981), indicates an age about 104 Ma, which is indistinguishable from the minimum age of the dike swarm. The pluton is cut by Independence dikes, and a U-Pb zircon age (Chen and Moore, 1982) suggests that the pluton crystallized at least 160 Ma. The biotite and hornblende ages are discordant, and the K_2O content of the hornblende is twice that characteristic of Sierra Nevada hornblende. This hornblende, like the hornblende in sample S, may have undergone potassium metasomatism. Shearing and concomitant alteration may have altered the composition of this hornblende and emplacement of younger plutons nearby reset its radiometric clock.

The age determination for sample L, collected well within the Taboose pluton, indicates crystallization about 83 Ma, but mapping by Moore (1963) shows that the pluton's west edge is cut by Independence dikes. The absence of mafic dikes elsewhere in the Taboose pluton, the uncertain nature of the contact, and the compositional similarity between the adjacent alaskite of Red Mountain and the Taboose pluton suggest that the location of the contact as mapped by Moore (1963) is at least 1 km west of its actual location. Thus, the mapped mafic dikes cut the older alaskite of Red Mountain but not the Taboose pluton. The age determined for the Taboose pluton may be a crystallization age, rather than a reset age.

Ages for hornblende (about 126 Ma) and biotite (about 69 Ma) from the Lower Jurassic Tinemaha Granodiorite (sample I), are discordant. Other K-Ar age determinations for the Tinemaha Granodiorite (Kistler and others, 1965), however, indicate that the unit may have crystallized about 180 Ma and probable correlative intrusives have U-Pb ages of about 165 Ma (Chen and Moore, 1982). The cause for the discrepancy between the various age determinations for the Tinemaha Granodiorite are unknown although a thermal event that may have accompanied emplacement of the Cretaceous Inconsolable Granodiorite about 98 Ma (Kistler and others, 1965) may have caused argon loss from the Tinemaha Granodiorite.

Sample J was collected from a granodiorite correlated with the granodiorite of Tombstone Creek (Moore and Marks, 1972). U-Pb zircon age determinations for two samples from the southern end of the pluton, collected 1 km apart, indicate crystallization of 115 and 99 Ma, respectively (Chen and Moore, 1982). Lead isotopic data for the 115 Ma-old sample age are internally discordant; Chen and Moore (1982) suggested that the discordancy indicates inherited zircon. Data for the 99 Ma-old sample are fairly concordant. Hornblende from sample J gives an age of about 84 Ma, and biotite gives an age of about 82 Ma. The biotite-hornblende age concordance suggests that the K-Ar determinations give the pluton's crystallization age. However, the radiometric clocks in both biotite and hornblende may have been reset when younger plutons were emplaced around the granodiorite of Tombstone Creek. The discrepancy between the U-Pb zircon ages and the K-Ar results may be accounted for in a variety of ways: The correlation of the dated sample with the granodiorite of Tombstone Creek may be incorrect; or the granodiorite may have had a prolonged cooling history between 99 and 84 Ma, which could have inhibited argon retention in both biotite and hornblende; or the biotite-hornblende data indicate crystallization age and the zircon sample that gave the 99 Ma age, like the other zircon sample, could contain older, inherited zircon. However, the near concordance of the lead isotopic data suggests that this sample probably does not contain significant inherited zircon.

The lithologic similarity and proximity of the quartz monzonite of Mono Recesses and the quartz monzonite of Turret Peak suggest that they may be connected at depth (Lockwood and Lydon, 1975). The two units crop out several kilometers apart and are separated by the Upper Cretaceous Lamarck Granodiorite. Ages for biotite (about 76 Ma) and hornblende (about 82 Ma) from the quartz monzonite of Turret Peak, sample F, are in agreement with those of Evernden and Kistler (1970) for the quartz monzonite of Mono Recesses. Thus, the quartz monzonite of Turret Peak may be an apophysis of the Mono Recesses pluton. If so, this is one of the few places in the Sierra Nevada batholith where part of a pluton is exposed as an apophysis, separate at the current level of exposure, from the main mass of the pluton.

Ages for biotite (about 81 Ma) and hornblende (about 95 Ma) from the granodiorite of Mount Reinstein (sample G) and for biotite (about 83 Ma) from the quartz monzonite of Finger Peak (sample H), respectively, were determined to evaluate the hypothesis that these plutons constitute a comagmatic, concentrically zoned intrusive suite. According to this hypothesis, the granodiorite of Mount Reinstein crystallized from early, relatively primitive magma; whereas, the quartz monzonite of Finger Peak crystallized from more evolved, younger magma. Age spans of 5–10 Ma determined by Stern and others (1981) for comagmatic suites of the central Sierra Nevada suggest that the 14 Ma age span between crystallization of the quartz monzonite of Finger Peak and the granodiorite of Mount Reinstein is too great and precludes a comagmatic relationship. Comparison of sample H biotite age with sample G hornblende age might be inappropriate if the biotite age was reset. However, the plutons adjacent to the quartz monzonite of Finger Peak, including the Upper Cretaceous Mount Givens Granodiorite and the plutons of the Goddard pendant, are all older than the quartz monzonite of Finger Peak (Stern and others, 1981; Chen and Moore, 1979) and thus could not have caused reheating and argon loss from sample H biotite. Furthermore, the granodiorite of Mount Reinstein (sample G) biotite-hornblende age discordance may be attributable to reheating of the Mount Reinstein biotite during emplacement of the quartz monzonite of Finger Peak. We conclude that the granodiorite of Mount Reinstein and the quartz monzonite of Finger Peak are not members of a comagmatic suite.

Age determinations for samples Q and P suggest that the Spook pluton crystallized about 76 Ma and was, therefore, one of the last plutons to be emplaced in the Sierra Nevada batholith. The pluton is located on the eastern edge of the batholith near some of the oldest plutons. This instance of temporal juxtaposition contrasts with age-belt patterns described by Evernden and Kistler (1970), Chen (1977), and Moore and others (1979). Whether anomalous bodies, such as the Spook pluton, exist within an otherwise orderly age-belt pattern or whether the Sierra Nevada batholith evolved in a time-space random pattern will be determined only by additional geochronologic investigations.

Among the biotite-hornblende pairs that are discordant and for which there is no specific geologic evidence that might account for the discordance are samples C, F, G, R, T, V, and Y. Biotite from these samples may have lost argon with or without the influence of thermal events that occurred subsequent to cooling through the argon retention temperature for biotite. Determinations based on hornblende indicate minimum crystallization ages because the hornblende may have undergone some argon loss as well. Intrusive age relationships and radiometric ages of nearby plutons provide permissive corroboration of the hornblende ages determined for these samples.

SUMMARY

On the basis of evidence from geologic relations and geochronologic studies by Evernden and Kistler (1970), Chen (1977), Chen and Moore (1979, 1982) and Stern and others (1981), it is probable that a number of the biotite ages determined in this study are too young. Pluton ages based on biotite separates alone, that lack substantiation either in field relations or other geochronologic evidence, are usually minimum ages. Concordant biotite-hornblende pairs, however, suggest that a close approximation to the crystallization age may have been achieved (Dalrymple and Lanphere, 1969).

Many of the samples dated in this study and many previously reported ages for plutons of the Sierra Nevada batholith are of Late Cretaceous age. It is noteworthy that between about 80 and 90 Ma a major thermal event reset the K-Ar clock of many of the batholith's older plutons. The thermal event may be associated with the emplacement elsewhere within the batholith of the Cathedral Peak-type granitoids including the Sonora Pass pluton (Slemmons, 1953), the Upper Cretaceous Tuolumne Intrusive Suite (including the Cathedral Peak Granodiotite) (Stern and others, 1981), the Mono Recesses pluton (Evernden and Kistler, 1970), the Whitney Granodiorite (Evernden and Kistler, 1970), the granite of White Mountain (du Bray and Dellinger, 1981) (sample X, table 3), and the Isabella Granodiorite (Bergquist and Nitkiewicz, 1982). These plutons, which are among the largest in the range, extend almost continuously from the north end to the south end of the batholith, and were emplaced about 80 Ma. The heat that accompanied their emplacement probably had a profound effect throughout the eastern part of the batholith.

The tectonic events that triggered generation and emplacement of the Cathedral Peak-type magmas, all the same age, modal composition, texture, and chemistry, are not well known. Subduction dynamics, including shallowing of dip along the Benioff zone, at the edge of the Cretaceous North American plate may be partially

responsible for the great pulse of Late Cretaceous magmatism in the Sierra Nevada. The onset of low-angle subduction may also be responsible for the abrupt termination of magma generation in the Sierra Nevada region that followed production of the Cathedral Peak-type granitoids. Generation of these distinctive plutons, followed by an abrupt end to magma generation in the region suggests that the conditions that produced these plutons are characteristic of the Sierra Nevada batholith and its tectonic regime during Late Cretaceous time.

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