TABLE 3

Summary of Rb and Sr analyses on Petersburg Granite samples

Element	Average content, 12 weathered samples	Average content, 17 fresh samples	Average, weathered/fresh
Rb	263 ppm	218 ppm	1.21
Sr	77 ppm	106 ppm	0.73
Rb/Sr	3.42	2.06	1.66

The Rb and Sr X-ray fluorescence and isotope dilution analyses are summarized in table 3. (Eighteen additional fresh samples were analyzed for approximate Rb/Sr ratios by sawing smooth surfaces on specimens and analyzing these surfaces by X-ray fluorescence. The 18 fresh samples have an average Rb/Sr ratio of approximately 2.3 which is close to the value of 2.06 given in table 3. These additional results support our belief that 2.06 is the approximate Rb/Sr ratio for the unweathered Petersburg Granite.) The average Rb/Sr ratios for the 13 samples selected for additional chemical analyses (table 2) are in good agreement with the data for all 29 samples (table 3). This agreement indicates that the 13 samples are representative of the larger sampling of the granite.

CONCLUSION

Rb-Sr analyses of the Cape Ann Granite from Massachusetts and the Petersburg Granite from Virginia indicate that weathering readily visible in hand specimen has lowered the Rb-Sr whole-rock ages. However, the Rb-Sr whole-rock ages have been lowered only by approximately 10 percent. These results suggest that incipient weathering should not significantly affect the Rb-Sr whole-rock age of granitic rocks. If additional studies show that Rb-Sr whole-rock ages are consistently lowered by about 10 percent due to weathering, useful age data might be obtained on weathered granitic rock. Analyses of weathered granitic rocks would be especially useful in areas such as the southeastern United States where in places it is very difficult or impossible to obtain fresh samples.

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K-Ar AGES AND TIME SPAN OF EMPLACEMENT OF THE BOULDER BATHOLITH, MONTANA†

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ABSTRACT. K-Ar ages of biotite and hornblende from the composite Boulder batholith and satellitic masses range from 78 to 68 m.y. A statistical analysis of the data based on mean ages of the batholith units suggests that the emplacement of the batholith could have taken as little as 5 m.y. (76-71 m.y.). However, even though the isotopic age data generally support the sequence of intrusion inferred from field relations, reduction of K-Ar ages (particularly of biotite) of older rocks in the vicinity of younger plutons is suspected. On the assumption that maximum ages are more meaningful geologically when possible post-emplacement reheating is a factor, we interpret the available data to indicate that the total time of emplacement may have been about 9 m.y. (78-69 m.y.) and that the bulk (~ 90 percent) of the batholith was probably emplaced during the first 6 m.y. (78-72 m.y.). The youngest prebatholith rocks, the Elkhorn Mountains Volcanics, have isotopic ages of ~78 m.y. but may be slightly older. If so, the total time of emplacement could even be as great as 10 to 12 m.y.

INTRODUCTION

Rocks of the Boulder batholith were first radiometrically dated by Chapman, Gottfried, and Waring (1955) using the lead-alpha method and by Folinsbee and Reynolds (*in* Knopf, 1956) using the K-Ar method on K-feldspar. During the past decade, these pioneer geochronometric investigations have been supplemented by more than 50 K-Ar age determinations on biotite and hornblende from rocks of the batholith and satellitic bodies. The abundant K-Ar ages now available, together with geologic evidence, provide a means of estimating the time span of emplacement of the batholith.

The K-Ar age of a mineral from an intrusive rock unaffected by postemplacement phenomena records the time at which the rock cooled below the temperature required for complete retention of radiogenic argon by that mineral. If the intrusive body cools rapidly, the K-Ar ages of the minerals approximate the actual time of emplacement and crystallization. The relatively shallow depth (< 1-2 miles) of emplacement of the Boulder batholith, inferred from stratigraphic and structural relationships, permits the assumption that cooling was probably rapid for the batholith, so that the K-Ar ages obtained on biotite and hornblende probably approximate emplacement ages.

Knopf (1964), basing his conclusions on K-Ar ages of minerals in rocks from the northern part of the batholith, estimated the time span of emplacement of the Boulder batholith to be 7 to 8 m.y. The new isotopic ages presented herein, representing the whole of the batholith, suggest that the bulk (~ 90 percent) of the batholith was emplaced and cooled below the temperature required for complete retention of radiogenic argon in biotite and hornblende in about 6 m.y. (78-72 m.y.). However, a total time span of emplacement of about 10 to 12 m.y. cannot be ruled out.

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GEOLOGIC SETTING

The Boulder batholith, exposed throughout some 2200 square miles in southwestern Montana, intrudes rocks ranging from Precambrian (pre-Beltian) to Late Cretaceous in age. The youngest rocks intruded by the batholith are the Elkhorn Mountains Volcanics of Late Cretaceous age (Klepper, Weeks, and Ruppel, 1957, p. 37). They are largely or wholly Campanian. The batholith is unconformably overlain and locally injected by Lowland Creek Volcanics (Smedes, 1962), recently reassigned to the early Eocene by Smedes and Thomas (1965) on the basis of K-Ar ages on biotites (48-50 m.y.). The age of the batholith is thus established on geologic and geochronometric grounds as very late Cretaceous or Paleocene.

The composite nature of the Boulder batholith has been described by Knopf (1957), Klepper (ms), Smedes and others (1962), Becraft, Pinckney, and Rosenblum (1963), Ruppel (1963), Tilling (1964), and Smedes (1966). Rocks of the batholith range in composition from syenogabbro to alaskite, but approximately 90 percent of the exposed part is quartz monzonite or granodiorite (with 30-50 percent plagioclase, 15-30 percent K-feldspar, 20-30 percent quartz, and 10-15 percent biotite and hornblende). More than two-thirds of exposed rock constitutes a single large body, the Butte Quartz Monzonite, which is the host rock of the rich copper deposits at Butte in the southern end of the batholith. Detailed mapping in recent years has clearly demonstrated that the Butte Quartz Monzonite is coextensive with and indistinguishable from the Clancy Granodiorite (Knopf, 1963) in the northern end of the batholith. The correlation, based on complete physical continuity, of the Butte and Clancy rocks is further supported by the similarity of the isotopic compositions of lead in the K-feldspars of these two rocks (Doe, Tilling, and Klepper, 1965).

Numerous petrographic facies have been mapped within the large Butte mass (see, for example, the geologic map of Becraft, Pinckney, and Rosenblum, 1963; Ruppel, 1963). Most of these facies, based primarily on slight textural and/or compositional differences, are in subtle gradational rather than sharp contact with typically coarse-grained Butte rocks that have a color index of about 15. In fact, Becraft, Pinckney, and Rosenblum (1963, p. 8) stated: "Despite slight but mappable textural and compositional differences, all the rocks that constitute the Butte Quartz Monzonite, except possibly three fine-grained types, are considered part of a single large pluton". Subsequent and continuing field and laboratory work indicates that some of the finer grained facies, volumetrically quite subordinate, may indeed be equivalents of the geologically and geochronometrically established younger leucocratic plutons. However, the preponderance of data strongly suggests that no large intrusive masses of distinctly younger or older age are included within the Butte Quartz Monzonite (as generalized in fig. 1), which apparently crystallized as a relatively homogeneous body with local textural and minor compositional differences.

Field relations indicate that small masses of syenogabbro, syenodiorite, and melamonzonite ("mafic rocks" in fig. 1) are consistently the oldest batholithic rocks. Next in the intrusive sequence are the plutons of relatively dark colored granodiorites composing the Rader Creek pluton (Tilling, 1964) and the Burton Park pluton (Smedes, 1967) near the southern end of the batholith and the Unionville Granodiorite (Knopf, 1963) near the northern end. These rocks are cut by the lighter colored Butte Quartz Monzonite. The Butte Quartz Monzonite, its silicic facies (as at Homestake and Pulpit Rock), and abundant bodies of alaskite form a continuous, genetically related series, as shown by close petrographic similarity and by both crosscutting and gradational contacts between different rock types. At any locality, however, the more felsic of the two rocks in contact is generally the younger. The silicic facies of the Butte Quartz Monzonite, for example the Pulpit Rock and other small plutons elsewhere in the batholith (see fig. 1), generally grade into but locally cut the main mass of the Butte Quartz Monzonite.

Last in the intrusive sequence are the leucocratic granodiorites and quartz monzonites of the Donald, Hell Canyon, Moose Creek, and Climax Gulch plutons in the southern part of the batholith and the plutons of biotite adamellite and biotite granite (of Knopf, 1963) in the northern part. Rocks of the Donald and Climax Gulch plutons cut the Butte Quartz Monzonite. The Hell Canyon and Moose Creek masses are not in contact with other batholith rocks; their position in the intrusive sequence is inferred on the basis of lithologic similarity and proximity to the Donald mass.

The Boulder batholith is fringed by many small satellitic intrusive masses, which range in composition from syenogabbro to silicic quartz monzonite; most of these masses are relatively homogeneous, but a few are composite. Because they are intruded into country rock of different ages, the satellitic plutons cannot be fit into the intrusive sequence of the batholith on geologic evidence. Nonetheless, the limited isotopic age data support the inference from field relations and petrographic similarities that these plutons were emplaced during the same time span as the batholith.

DISCUSSION OF RESULTS

K-Ar ages of biotites and hornblendes of the Boulder batholith and satellitic stocks from all available published and unpublished works are presented in tables 1, 2, and 3 and are plotted against the sequence of plutonism as determined by field relations in figure 2. The geographic locations of the dated rocks are plotted (in approximate numerical order from north to south) on a generalized geologic map of the batholith (fig. 1). Analytical techniques used in this study are similar to the techniques generally used in K-Ar geochronology outlined in detail elsewhere (Kistler, Bateman, and Brannock, 1965; Evernden and Curtis, 1965). The

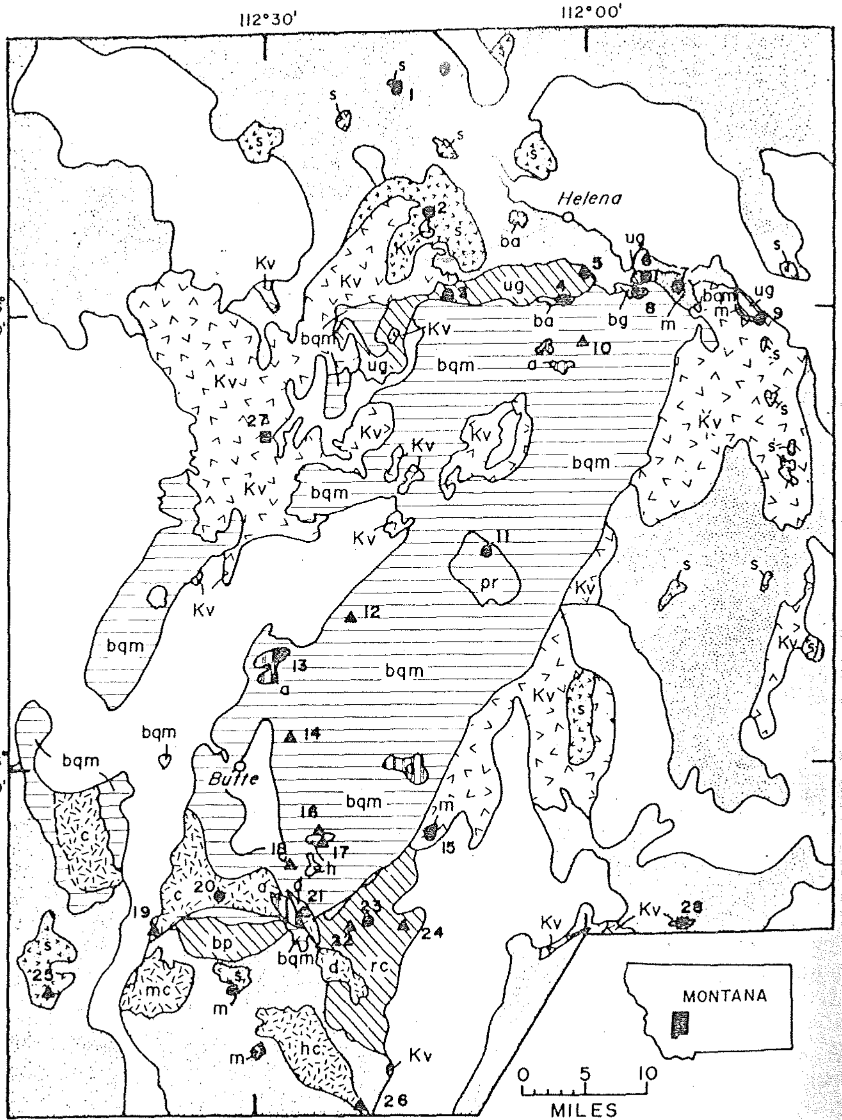
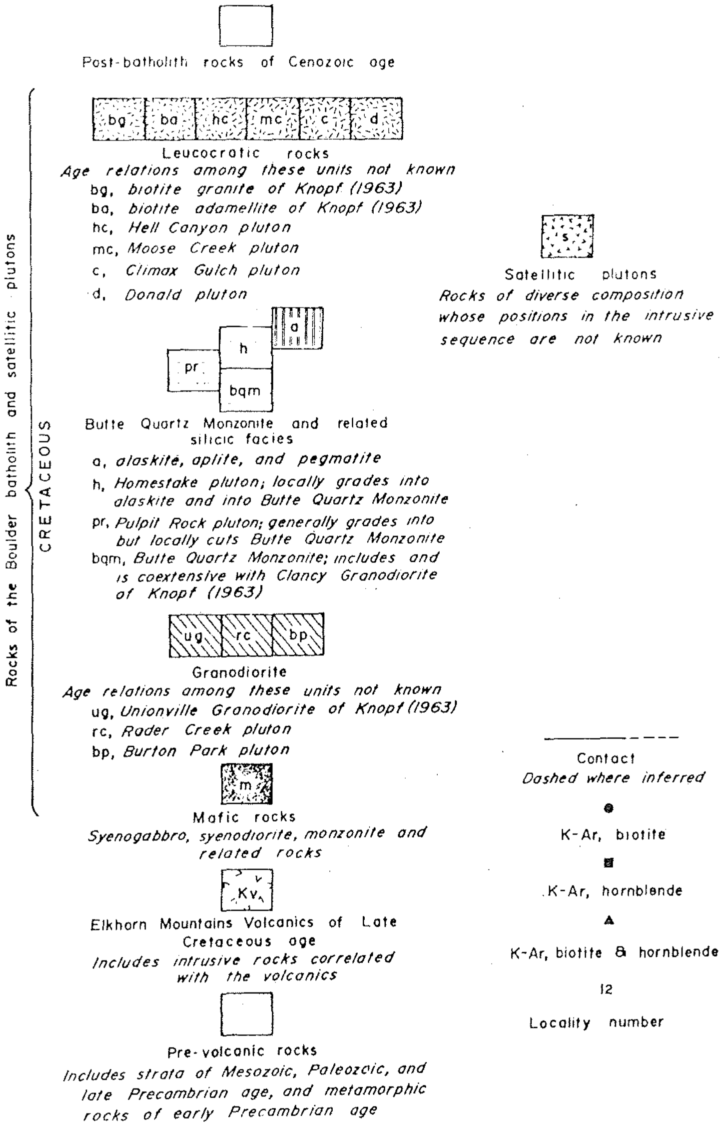


Fig. 1. Generalized geologic map of the Boulder batholith and vicinity showing location of rocks dated by the K-Ar method.

Explanation of Figure 1



constants utilized for K-Ar age determinations and the analytical uncertainties are included in tables 1 and 2.

The recent work of Hart (1964) and Kistler, Bateman, and Brannock (1965) shows that diffusion losses of radiogenic argon, resulting in reduced K-Ar ages, can be particularly significant when older rocks are reheated by younger intrusives. Both these studies indicate that biotite is particularly susceptible to thermal effects of a nearby younger intrusive. Indeed the K-Ar age of biotite in an intruded rock may be significantly lowered even at distances from the contact as great as the width of the intruding mass. Hornblende in the vicinity of a younger intrusive is much less susceptible to argon loss. Hart (1964) found that the K-Ar ages of hornblende in intruded Precambrian rock are virtually unaffected beyond a distance of one one-hundredth of the width of the small intruding Tertiary stock (approx. 2 miles in diam). Kistler, Bateman, and

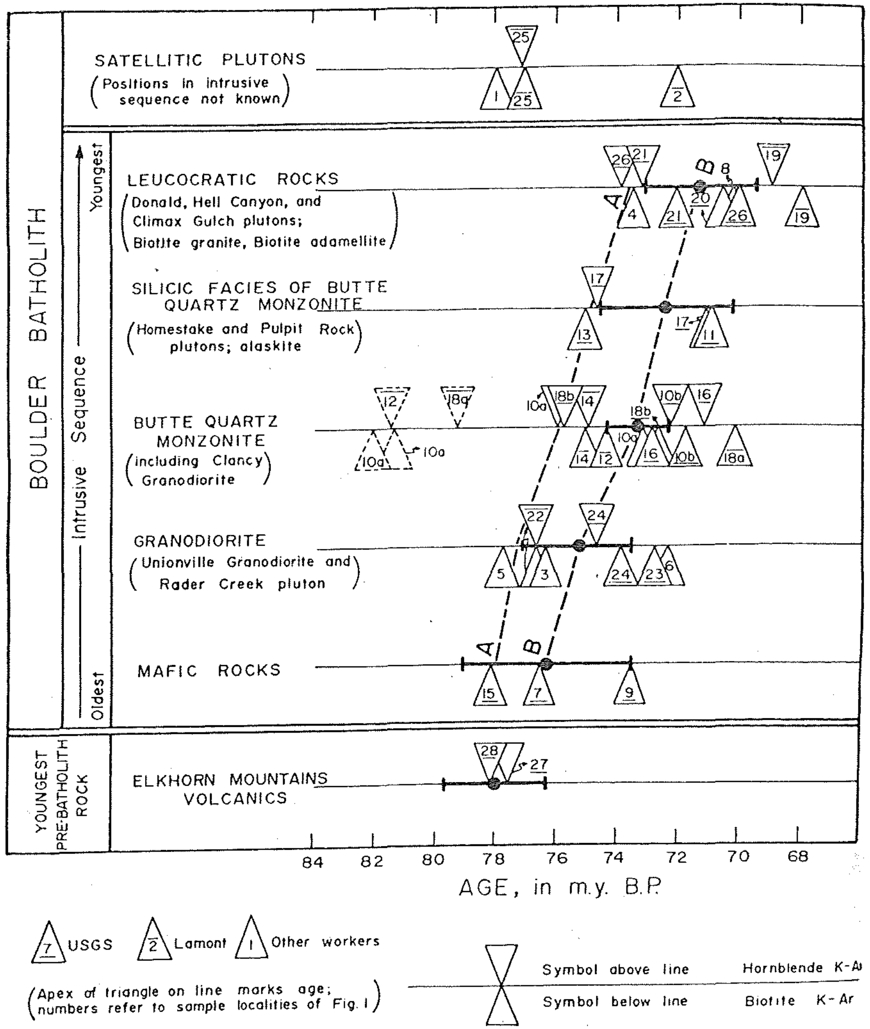


Fig. 2. K-Ar ages of the Boulder batholith and of the Elkhorn Mountains Volcanics. Ages of batholith rocks are grouped according to position in the intrusive sequence as determined by field relations. Ages indicated by dashed triangles are considered anomalous (see text); for samples with replicate determinations (see table 3), the average value is plotted. The curve AA may approximate the *beginning* times of emplacement of the groups of the dated plutons, if postemplacement reduction of ages has occurred. Curve BB links the mean ages (shown as |—●—|) of the various groups of rocks; bars give error of the mean at the 95 percent confidence level.

Brannock (1965), dealing with intrusive masses of batholithic dimensions in the Sierra Nevada, show, however, that loss of argon from hornblende may be significant as far away from the contact as half the width of the intruding mass.

Thus it is clear that the thermal effect of later intrusions must be considered in assessing the isotopic age of any pluton in a composite batholith such as the Boulder batholith or of any rock cut by younger igneous rocks. As will be evident from the discussion to follow, an unknown number of the isotopic ages for the Boulder batholith may well be reduced ages (resulting from postemplacement reheating by later intrusions).

Elkhorn Mountains Volcanics.—A precise fix on the age of the Elkhorn Mountains Volcanics, the youngest rocks cut by the oldest rocks of the batholith, is essential to establish the limits of time of inception of batholith emplacement. Hornblende K-Ar ages of approximately 78 m.y. were obtained on samples from the lower member of the Elkhorn Mountains Volcanics (of probable early Campanian age on geologic grounds) at two widely separated localities (nos. 27, 28, fig. 1). Locality 27 is at least 3000 feet above the base of the volcanics and approximately 5 miles from the nearest exposed batholith rocks. No estimate of the vertical separation from the roof of the batholith can be given for locality 28 which is about 12 miles north of the nearest exposure of the Tobacco Root batholith (not shown on fig. 1); two biotites from this batholith have K-Ar ages of 75 and 52 m.y. (Giletti, 1966). The remoteness of locality 28 from any exposed batholithic rocks minimizes the possibility that later thermal events have affected its age.

Assuming that the isotopic age of the volcanic rocks has not been reduced by later thermal events, the time of inception of batholith emplacement can be no earlier than 78 ± 1.7 m.y. (error of the mean given at the 95 percent confidence level). If, on the other hand, the K-Ar ages have been reduced by heat of the batholith, the earliest permissible time for the inception of emplacement would be about 81 m.y., and the latest would be about 78 m.y., on the basis of the early Campanian time point given by Gill and Cobban (1966, table 2).

Mafic rocks.—Age determinations of the mafic masses, the oldest rocks of the batholith, range from 73 to 78 m.y. As these plutons intrude the Elkhorn Mountains Volcanics, the maximum age probably does not exceed 78 m.y. and cannot exceed 81 m.y. The age for sample at locality 9 (73 m.y.) almost certainly is a minimum, because this is within a quarter mile of the margin of a younger intrusive mass whose diameter is approximately 2.5 miles.

Granodiorite (Unionville Granodiorite and the Rader Creek pluton).—These granodiorite plutons intrude rocks as young as the middle member of the Elkhorn Mountains Volcanics and are intruded by the Butte Quartz Monzonite and/or younger rocks. The K-Ar ages of these two plutons range from 72 to 78 m.y. Because all the dated rocks are within 5 miles (that is, < than half the width) of the intruding Butte Quartz Monzonite, the ages obtained may have been reduced by reheating, judging from the work of Kistler, Bateman, and Brannock (1965). The fact that ages of paired biotite and hornblende from two Rader Creek samples are concordant, however, suggests that the range 74 to 77 m.y. approximates the time of emplacement of these rocks. An alternative

TABLE 1

K-Ar isotope ages, U. S. Geological Survey data

Igneous unit	Locality no. (fig. 1)	Mineral	%K_2O	% Radiogenic argon ($*Ar^{40}$)	$*Ar^{40} \times 10^{-10}$ moles/g	Age (m.y.)	Source*
Elkhorn Mountains Volcanics (Kv), Lower unit	27	Hornblende	0.988***	90	1.155	77.6 ± 2.4	1
	28	Hornblende	0.829***	94	0.975	78.8 ± 2.4	1
		Hornblende	0.834***	95	0.984	77.6 ± 2.4	1
Mafic rocks (m)	7	Biotite	9.54‡	93	10.88	75.8 ± 3.8	2
		Biotite	9.24	91	10.77	77.4 ± 3.1	1
	9	Biotite	8.82	91	9.76	73.5 ± 2.9	1
	15	Biotite	8.75	89	10.31	78.2 ± 3.1	1
Granodiorite							
Rader Creek pluton (rc)	23	Biotite	8.84‡	92	9.68	72.8 ± 3.6	2
	24	Biotite	6.79‡	82	7.55	73.9 ± 3.7	2
		Hornblende	0.476	60	0.535	74.7 ± 3.0	1
Butte Quartz Monzonite (bqm) (includes Clancy Granodiorite)	10b	Biotite	8.74	96	9.42	71.7 ± 2.3**	1
		Biotite	8.74	96	9.45	71.9 ± 2.2	1
		Hornblende	0.456***	84	0.503	73.3 ± 2.5	1
		Hornblende	0.459***	70	0.492	71.4 ± 2.5	1
	16	Biotite	7.33‡	86	8.08	72.9 ± 3.6	2
		Hornblende	0.550	69	0.589	71.2 ± 3.6	1
	18b	Biotite	9.00	74	9.84	72.7 ± 3.0	1
		Hornblende	0.600***	57	0.691	76.5 ± 2.4	1
		Hornblende	0.602***	72	0.680	75.0 ± 3.4	1
Silicic facies of Butte Quartz Monzonite (including alaskite)							
Pulpit Rock pluton (pr)	11	Biotite	9.10‡	89	9.84	71.9 ± 3.6	2
		Biotite	9.10‡	87	9.59	70.2 ± 3.5**	2
Alaskite (a)	13	Biotite	8.61‡	86	9.73	75.1 ± 3.7	2
Homestake pluton (h)	17	Biotite	8.61‡	90	9.13	70.5 ± 3.5	2
		Biotite	8.61‡	91	9.28	71.7 ± 3.3**	1
		Hornblende	0.399***	63	0.449	74.7 ± 2.6	1

TABLE 1 (Continued)

Igneous unit	Locality no. (fig. 1)	Mineral	%K_2O	% Radiogenic argon ($*Ar^{40}$)	$*Ar^{40} \times 10^{-10}$ moles/g	Age (m.y.)	Source*
Leucocratic rocks							
Climax Gulch pluton (c)	20	Biotite	7.92‡	85	8.34	70.6 ± 3.5	2
Donald pluton (d)	21	Biotite	7.91	86	8.35	70.2 ± 3.5	2
		Biotite	7.91	93	8.80	74.0 ± 3.0**	1
		Hornblende	0.417***	79	0.459	73.2 ± 2.5	1
Hell Canyon pluton (hc)	26	Biotite	8.21‡	90	8.65	70.1 ± 3.5	2
		Hornblende	0.486	71	0.540	73.9 ± 3.0	1

* (1) John D. Obradovich, U. S. Geol. Survey, Denver, Colorado, 1965 and 1966.
(2) Richard Marvin and Herman Thomas, U. S. Geol. Survey, Washington, D. C., 1963.

** Replicate argon analyses.

*** Replicate potassium analyses, isotope dilution.
‡ Single potassium analysis, flame photometer.
} All other potassium analyses in replicate, flame photometer.

All ages have been calculated using the following constants:

$$\lambda_e = 0.584 \times 10^{-10}\ YR^{-1}$$
$$\lambda_\beta = 4.72 \times 10^{-10}\ YR^{-1}$$
$$K^{40} = 1.19 \times 10^{-4} \text{ atomic abundance}$$

TABLE 2

K-Ar isotope ages, data of McDowell (1966)

Igneous unit	Locality no. (fig. 1)	Mineral	$\%K_2O$	% Radiogenic argon ($*Ar^{40}$)	$*Ar^{40} \times 10^{-10}$ moles/g	Age (m.y.)
Satellitic plutons (s)						
	2	Biotite	8.55	78	9.39	73.0 ± 2.9
		Biotite	8.65	83	9.26	71.2 ± 2.8
	25	Biotite	7.02	57	8.16	77.1 ± 3.1
		Hornblende	0.548	56	0.637	77.2 ± 3.1
Granodiorite						
Rader Creek pluton (rc)	22	Biotite	6.89	79	7.96	76.7 ± 3.1
		Hornblende	0.836	46	0.966	76.7 ± 3.1
Butte Quartz Monzonite (bqm)	12	Biotite	8.95	89	10.22	75.8 ± 3.0
		Biotite	8.95	93	9.84	73.1 ± 2.9*
		Hornblende	0.625	39	0.769	81.5 ± 3.3
	14	Biotite	8.30	79	9.38	75.1 ± 3.0
		Hornblende	0.520	53	0.587	75.0 ± 3.0
	18a	Biotite (> 20 mesh)	7.64	87	8.09	70.4 ± 2.8
		Biotite (60-80 mesh)	5.99	57	6.33	70.3 ± 2.8
		Hornblende	0.575	78	0.697	80.4 ± 3.2
		Hornblende	0.575	13	0.678	78.2 ± 3.1
Leucocratic rocks						
Climax Gulch pluton (c)	19	Biotite	8.33	82	8.50	68.0 ± 2.7
		Hornblende	1.29	69	1.337	69.0 ± 2.8

* Replicate argon analyses.

interpretation of these concordant biotite-hornblende age pairs is that both Ar^{40}/K^{40} ratios have been reduced by the younger Butte Quartz Monzonite essentially to the same level. This is less likely because of the marked differences between hornblende and biotite in argon retentivity upon reheating.

Butte Quartz Monzonite (including Clancy Granodiorite).—The Butte Quartz Monzonite intruded and metamorphosed rocks as young as the upper unit of the Elkhorn Mountains Volcanics (Campanian). K-Ar ages reported for the Butte Quartz Monzonite range from 70 to 82 m.y., and age determinations of one of the rocks from this pluton—the "type" Clancy Granodiorite at Kain Quarry (loc. 10a, fig. 1)—by several investigators (Knopf, 1964) are strongly discrepant. The ages for the Kain Quarry rock are tabulated in table 3 (loc. 10a); ages of biotite from the same sample range from 73 to 82 m.y., with a single age determination on hornblende of 76 m.y. The differences in the biotite dates are due primarily to differences in the measurement of radiogenic argon content per gram of sample. In view of this discrepancy, we analyzed another sample of the homogeneous rock from the Kain Quarry. The resulting ages of ~ 72 m.y. for both hornblende and biotite from this sample (tables 1 and 3, loc. 10b) are in good agreement with the biotite age determined by Geochron Laboratories, Inc. (73.2 m.y.), as reported by Knopf (1964).

Ages determined by McDowell (ms) of hornblendes from two rocks (fig. 1, loc. 12—81.5 m.y.; loc. 18a, 78.2-80.4 m.y.) also exceed any of the ages obtained for even the oldest batholith rocks. If valid, these results would suggest that all other ages for the batholith are low because of a postemplacement disturbance affecting the entire batholith. To test this possibility we collected and dated a sample from the same outcrop where McDowell obtained no. 18a and two samples from the youngest prebatholith rocks (the Elkhorn Mountains Volcanics). The ages of the prebatholith volcanic rocks (both 78 m.y.) and their bearing on the onset of batholith emplacement have already been discussed (see p. 677). Our results of 75.0 ± 3.4 and 76.5 ± 2.4 m.y. (duplicate determinations) for the hornblende of the new sample (18b, table 1) are lower than the results of McDowell for hornblende (duplicate determinations—78.2 ± 3.1 and 80.4 ± 3.2 m.y.) from the same locality. Although a comparison of the analytical data (tables 1 and 2) suggests that the disparity between our results and those of McDowell stems principally from differences in the analysis for potassium, any one or several of the following possibilities may be contributive factors:

1. Experimental error may account for most, perhaps all, of the observed differences.

2. Because of systematic bias, not all laboratories will produce the same results for the same sample. McDowell obtained both the oldest and the youngest ages determined, thus suggesting that such systematic bias is not a major factor.

3. Sample preparation and splitting procedures (such as pouring or quartering) may result in incorrect Ar^{40}/K^{40} ratios. For example, if a hornblende sample has a few percent admixed biotite, the biotite may be concentrated in either the argon or the potassium fraction and, if concentrated in the argon fraction, would result in an anomalously high age. To minimize such problems, we employed a multichanneled microsplitter.

4. A characteristic feature of the Butte Quartz Monzonite is its high content of hornblende-rich mafic inclusions relative to the other plutons of the batholith. If these inclusions are of significantly older age and were not completely degassed at the time of their incorporation by the Butte magma, then the presence of xenocrystic hornblende in the sample would also produce an anomalously high age. Great care was excercised in collecting the sample at locality 18b to avoid this problem.

Because our ages for the Elkhorn Mountains Volcanics and the Butte sample at locality 18b are consistent with geologic relations but at variance with McDowell's hornblende ages, McDowell's ages are considered to be anomalous, whatever the cause.

The range in ages (76-70 m.y.) for the Butte Quartz Monzonite (excluding the anomalously high values discussed above) do not indicate the actual span of emplacement of this large pluton. The youngest ages obtained almost certainly have been reduced by the thermal effect of younger intrusives, several of which (samples at locs. 4, 13, 17, 21, and 26) are as old as 75 m.y. For example, the ~ 72 m.y. age for the Butte sample at locality 16 probably is due to its proximity (less than half a mile) to the younger Homestake pluton (see figs. 1 and 2). The lower than expected ages (~ 72 m.y.) for the sample at locality 10b (the Kain Quarry rock discussed earlier) cannot be explained by proximity to sizeable younger intrusives but may be accounted for, in part, by the higher incidence (relative to other localities of rocks dated from the same mass) of small bodies of aplitic rocks, quartz latite and rhyolite dikes, chalcedony veins, and zones of hydrothermal alteration and silicification (see the maps of Becraft, Pinckney, and Rosenblum, 1963, and of Smedes, 1966). Thus, the actual time of emplacement of the Butte Quartz Monzonite is probably best approximated by the ages in the range 76 to 74 m.y. of the dated rocks (samples at locs. 12, 14, and 18b) which apparently have been unaffected or least affected by postemplacement phenomena.

Silicic facies of the Butte Quartz Monzonite.—Many small to moderate-sized dikes, sheets, and irregular bodies of silicic rocks in places grade into and in places crosscut the Butte Quartz Monzonite and are genetically related to it. Field and petrographic evidence suggests that these rocks crystallized from local concentrations of residual Butte Quartz Monzonite magma rather than from separate batches of younger magma. Only one hornblende age is available for these rocks—the 74.7 m.y. age for the Homestake pluton (loc. 17, fig. 1). Biotite ages of these silicic facies of the Butte Quartz Monzonite fall in the range 75 to 70 m.y.

Leucocratic rocks.—The youngest rocks of the Boulder batholith include the biotite granite and biotite adamellite of Knopf (1963) and the Donald, Hell Canyon, Moose Creek, and Climax Gulch plutons (see fig. 1). Although contact relations have not been observed between these leucocratic rocks and silicic facies of the Butte Quartz Monzonite, the younger relative age of the leucocratic rocks is inferred from indirect evidence: (1) many bodies of rocks of the silicic facies of the Butte Quartz Monzonite are gradational into Butte rocks, whereas leucocratic rocks always have sharp contacts with the Butte rocks; and (2) aplites and alaskites are rare in these leucocratic rocks, except in the Climax Gulch pluton, but are abundant in the silicic facies of the Butte Quartz Monzonite. Ages of the leucocratic rocks range from 68 to 74 m.y. Ages of 68 to 70 m.y. for the Climax Gulch pluton and the 70 m.y. age for the biotite granite of Knopf (1963) suggest that sporadic plutonism may have persisted for 4 to 6 m.y. after the main mass of the batholith had been emplaced.

Satellitic plutons.—Because of their isolated occurrence in country rocks of diverse ages, it is impossible to rank the satellitic plutons in the intrusive sequence on geologic grounds. Isotopic ages of 77 to 78 m.y., however, indicate that two of the dated satellitic masses (locs. 1 and 25, fig. 1) are early in the intrusive sequence. The age (~ 72 m.y.) of a third mass (loc. 2, fig. 1) may be a minimum because of the presence nearby of a pluton (the porphyritic granodiorite of Knopf, 1963) which is inferred to be younger.

INTERPRETATION

Interpretation of the available isotopic age data (table 3) may be approached from two different viewpoints—one based solely on a statistical assessment of the data, the other, tempered by geologic relationships and by results obtained in prior geochronometric studies in composite batholiths or in regions characterized by multiple igneous and/or metamorphic events.

A statistical analysis of the data reveals that the standard deviation of a single analysis selected from the total data for the various batholith units is usually less than that stated for individual age determinations (compare table 4 with tables 1 and 2). This probably stems from overestimation of the analytical error of individual age determinations. In addition, an "F" test of the observed variances indicates that at the 95 percent confidence level the dispersion in the results could be entirely due to random errors in analysis, if all the samples were drawn from a single population having a coefficient of variation of 2.5 percent (see table 4).

A test based on the ratio of the mean square successive difference to the variance of means (see Crow and others, 1960, p. 63) demonstrates that the trend of the plotted mean ages (fig. 2) has significance at the 99.0 percent confidence level. An "t" test for significance of the difference of two means shows that the results for the Elkhorn Mountains Volcanics

TABLE 3

Isotopic ages of the Boulder batholith and of the prebatholith volcanics. Ages of the batholith rocks are listed according to intrusive sequence established geologically; oldest to youngest

Igneous unit	Sample no.	Locality no. (fig. 1)	Mineral	Age	Source*
1. Elkhorn Mountains Volcanics (Kv), Lower unit	D1564	27	H	77.6	1
	D1567	28	H	78.8	1
			H	77.6	1
2. Mafic rocks (m)	S1419	7	B	75.8	2
			B	77.4	1
	605-599	9	B	73.6	1
	63K-350	15	B	78.2	1
3. Granodiorite**					
Unionville Granodiorite (ug)		3	B	76.4	3
		5	B	77.8	3
		6	B	72.4	6
Rader Creek pluton (rc)	MB-1	22	B	76.7	8
			H	76.7	8
	61K-661	23	B	72.8	2
	61K-647	24	B	73.9	2
			H	74.7	1
4. Butte Quartz Monzonite (bqm) (includes Clancy Granodiorite)	AK-48	10a	B	82.1	4
			B	81.4	5
			B	73.2	3
			H	76.0	5
	63T-273	10b	B	71.7	1
			B	71.9	1
			H	73.2	1
			H	71.4	1
	MB-9	12	B	75.8	8
			B	73.1	8
			H	81.5	8
	MB-8	14	B	75.1	8
			H	75.0	8
	63K-306	16	B	72.9	2
			H	71.2	1
	MB-2	18a	B	70.4	8
			B	70.3	8
			H	80.4	8
			H	78.2	8
	D1566	18b	B	72.7	1
			H	76.5	1
			H	75.0	1
5. Silicic facies of Butte Quartz Monzonite (includes alaskite related to bqm)					
Pulpit Rock pluton (pr)	52C-45	11	B	71.9	2
			B	70.2	2
Alaskite (a)	62K00	13	B	75.1	2
Homestake pluton (h)	1K-241	17	B	70.5	2
			B	71.7	1
			H	74.7	1
6. Leucocratic rocks**					
Donald pluton (d)	W-21	21	B	70.2	2
			B	74.0	1
			H	73.2	1
Hell Canyon pluton (hc)	61K-633	26	B	70.1	2
			H	73.9	1
Biotite granite (bg)		4	B	73.5	3
Biotite adamellite (ba)		8	B	70.2	3
Climax Gulch pluton (c)	MB-7	19	B	68.0	8
			H	69.0	8
	60S-C3	20	B	70.6	2
7. Satellitic plutons (s)***		1	B	78.0	7
	MB-15	2	B	73.0	8
			B	71.2	8
	MB-6	25	B	77.1	8
			H	77.2	8

* 1. John D. Obradovich, U. S. Geol. Survey, Denver, Colorado.
2. Richard Marvin and Herman Thomas, U. S. Geol. Survey, Wash., D. C.
3. Geochron Lab., Inc., *in* Knopf, 1964.
4. Folinsbee *in* Knopf, 1964.
5. Evernden *in* Knopf, 1964.
6. Geochron (Knopf, 1964, written commun.).
7. Baadsgaard, Folinsbee, and Lipson, 1961.
8. McDowell, Lamont Observatory, 1966.

** Geologic age relationships between the members of this group cannot be determined because of their separated occurrences.

*** Relative positions of the satellitic plutons in the intrusive sequence are not known; placement on this group at end of table is arbitrary and has no age significance.

All ages have been calculated using the following constants:

$\lambda_\epsilon = 0.584 \times 10^{-10} \mathrm{YR}^{-1}$

$\lambda_\beta = 4.72 \times 10^{-10} \mathrm{YR}^{-1}$

$K^{40} = 1.19 \times 10^{-4}$ atomic abundance

and the mafic rocks are statistically different at the 70 percent confidence level but not the 80 percent level. This observation is compatible with geologic evidence indicating that the time gap between prebatholith volcanism and onset of plutonism was small indeed (Robinson, Klepper, and Obradovich, 1968).

The statistical test shows the difference between the means of the mafic rocks and leucocratic rocks is significant at the 99 percent confidence level; the difference between the means is 4.9 ± 3.0 m.y. (table 4; error given at the 95 percent confidence level). If the calculated error is considered, then an interval of 1.9 to 7.9 m.y. would encompass the total time of cooling of the first and last phases of the batholith through the critical isotherm for quantitative argon retention.

Implicit in the preceding statistical assessment, of course, are two fundamental suppositions:

1. Specimens from widely scattered localities within a single pluton or specimens from groups of contemporaneous plutons represent a valid (homogeneous) sample population.

2. The distribution of ages of any one pluton or group is strictly the result of random errors in analysis.

Both these suppositions are open to question for the following reasons:

A. Our defining of a single pluton or the grouping of contemporaneous plutons is based on field and petrologic criteria. Certitude of such field and petrologic control, however, obviously cannot be the same for every mapped body, depending on the quantity and quality of exposure, sampling density, number of mapping traverses, et cetera. Hence, for most geologic samples, a certain amount of inhomogeneity is inherent in the sample population.

B. In a composite plutonic mass such as the Boulder batholith, a finite degree of thermal disturbance of early plutons by intrusion of later plutons cannot be excluded and indeed might be expected. In other words, the Ar^{40}/K^{40} ratio of some samples may have been partially or totally reset. Even in the case of total resetting, however, the differences caused by thermal disturbance will not be great, if the differences in ages of successive intrusions are slight. If hornblende-biotite pairs were undisturbed, then a random distribution should result, that is, hornblende ages greater than, equal to, or less than biotite. However, the common relationship of hornblende ⩾ biotite age observed for the Boulder batholith and other composite batholiths is indicative of some resetting of Ar^{40}/K^{40} due to thermal disturbance. If resetting has occurred, then the assumption that all scatter of ages is due to random errors is invalid.

TABLE 4

Ranges, means, and errors of the mean of the K-Ar age determinations of the Boulder batholith and Elkhorn Mountains Volcanics (calculated from data of table 3)

Unit	Range (m.y.)	Mean* (m.y.)	Coefficient of variation** (%) of single analysis	Intrusive*** sequence
Leucocratic rocks	68.0-73.9	71.3 ± 1.6	3.1 (n=10)	Youngest
Silicic facies of Butte Quartz Monzonite	70.2-75.1	72.4 ± 2.2	2.9 (n=6)	↑
Butte Quartz Monzonite	70.3-76.5‡	73.2 ± 1.0	2.7 (n=17)	|
Granodiorite	72.4-77.8	75.2 ± 1.7	2.7 (n=8)	|
Mafic rocks	73.6-78.2	76.2 ± 3.1	2.7 (n=4)	Oldest
Elkhorn Mountains Volcanics	77.6-78.2	78.0 ± 1.7	0.9 (n=3)	

* Error of the mean given at the 95 percent confidence level and calculated using Student's "t" factor for limited sample population (Youden, 1951, p. 24).

** (n) is the number of age determinations within each group used to calculate the means and errors. All age determinations for a given group are used in the calculations, regardless of the fact that some may be duplicates; in a sense, the hornblende and biotite ages are duplicates for one sample, if they have not been disturbed (as is assumed in these calculations).

*** Established geologically; data for satellitic plutons are not included in this table, because their positions in the intrusive sequence are not known.

‡ Ages greater than 76.5 m.y. are excluded for reasons stated in text (p. 681-682).

Nonetheless, although the application of the statistical approach to this problem is open to question, the succession of mean ages of the various groups of plutons is in agreement with the geologically established intrusive sequence (table 4).

In the *Discussion of Results*, we have stated why we suspect that some of the samples may have been thermally affected. Therefore, we place greater significance on the oldest ages (both biotite and hornblende) of the oldest plutons that almost certainly have been thermally disturbed. Within this context, the grouping of ages around 78 m.y. for the Elkhorn Mountain Volcanics, mafic rocks, and granodiorite plutons would place a valid upper limit on the beginning of emplacement of the batholith. The concordant hornblende-biotite ages of 68 to 69 m.y. for the youngest leucocratic rocks may well represent the latest phase of plutonic activity. Thus, we interpret the total time span of the emplacement of the entire batholith to be about 9 m.y. (78-69 m.y.). However, since the youngest plutons of the batholith are volumetrically minor, the bulk of the batholith was emplaced in shorter time, perhaps about 6 m.y. (78-72 m.y.).

This interpretation rests on two key premises: (1) the best upper limit of the actual time of emplacement for any one pluton or group of geologically established penecontemporaneous plutons is the maximum age(s) (using either hornblende or biotite or both) obtained for that pluton or group of plutons; and (2) the time interval between the emplacement of a given pluton and its cooling to some low temperature to permit quantitative retention of radiogenic argon in biotite and hornblende is negligibly small compared to the time intervals between emplacement of successive plutons.

Premise (1) is supported indirectly by the generally good agreement between geochronometric data and known intrusive sequence—any overlapping of isotopic ages of two plutons is generally on the young side. Moreover, abundant data of Evernden and Kistler for the Sierra Nevada batholith (Kistler, oral commun., 1968) demonstrate that maximum K-Ar ages on undisturbed minerals from any pluton agree well with the whole rock Rb-Sr isochron age established for that pluton. Premise (2) appears well justified in view of the relatively shallow depth of emplacement of the composite Boulder batholith and of the narrow spread of K-Ar ages (both hornblende and biotite) observed for each of the constituent plutons.

Thus, within the context of the above-stated premises and excluding the anomalous high ages for samples at localities 10a, 12, and 18a for reasons stated previously (p. 681-682), we believe that the *beginning* of the time of emplacement of each pluton or group of plutons is closer to the curve AA than to curve BB on figure 2. Yet, the fact that both the curve for mean ages and that for maximum ages are nearly parallel and in good agreement with the intrusive sequence suggests that some of the dispersion of ages may well be due to random error. It is probable that the spread in ages for a given unit of the batholith, particularly those early in the intrusive sequence, reflects both random errors and systematic effects of postemplacement reheating.

In summary, regardless of the analytical uncertainties and possible interlaboratory biases, there is good agreement between the maximum or the mean ages of the various plutons and their positions in the geologically established intrusive sequence. On the assumption that many ages are somewhat reduced because of postemplacement reheating, the data suggest that the total time for emplacement of the composite Boulder batholith was not more than about 9 m.y. (78-69 m.y.), the bulk of the batholith, perhaps 90 percent, being emplaced during the first 6 m.y. (78-72 m.y.). However, if the ages ~ 78 m.y. obtained for the prebatholith volcanic rocks are minima, the total time of emplacement could be somewhat greater, perhaps as great as 10 to 12 m.y. However, on the assumption that the deviations in ages for the various plutons are due *entirely* to random error, the mean ages would indicate a time span of emplacement of 5 ± 3 m.y. (76-71 m.y.). The actual times of the beginning of emplacement of each pluton or group of contemporaneous plutons might best be represented by ages between curves AA and BB in figure 2.

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