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PALEOMAGNETISM OF THE LATE CRETACEOUS BOULDER BATHOLITH, MONTANA*

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ABSTRACT. Remanent magnetization data for 371 samples from 32 sites in major and satellitic plutons of the Boulder batholith, together with geologic, mineralogic, and geochronometric evidence, suggest the following: (1) Secondary magnetization components in mafic rocks and granodiorite, which were reheated during intrusion of the large Butte Quartz Monzonite body, may be removed by a.f. partial demagnetization. (2) The magnetic field during batholithic emplacement had, at various times, high and low inclination as well as normal and reversed polarity. (3) Some low-inclination magnetizations may reflect main dipole field movements to relatively stable positions where subsequent polarity reversal occurred, whereas others may represent short-lived excursions during field reversal. (4) The paleomagnetic pole for the Boulder batholith (73°N, 111°W) is not significantly different at the 95-percent level of confidence from the pole previously obtained for the Late Cretaceous Elkhorn Mountains Volcanics, the youngest rocks intruded. (5) A distinct north-south geographic separation of sites having normal and reversed polarity exists. (6) The Unionville Granodiorite and granodiorite of the Rader Creek pluton, once considered contemporaneous, cooled at distinctly different times in fields of opposite polarity. (7) Satellitic plutons were intruded throughout the time span of batholithic emplacement, which the magnetization data now suggest was closer to 10 m.y. than 5 m.y. (8) A field polarity sequence for the interval 68 to 78 m.y. shows four distinct reversed periods during batholithic emplacement and at least two periods of low field inclination. (9) The onset of multiple field reversals during emplacement of the Elkhorn Mountains Volcanics and early Boulder batholith rocks (about 78 m.y. ago), which was preceded by a 30-m.y. interval of predominantly normal field polarity, may prove to be a convenient time marker for the Late Cretaceous Epoch.

INTRODUCTION

Remanent magnetizations of the Boulder batholith and other associated intrusive rocks were first measured by Colville (ms) in a paleomagnetic reconnaissance of the northern Tobacco Root Mountains and vicinity, southeast of Butte, Montana. All 37 samples studied by Colville had normal magnetizations, and 15 from the batholith proper provided a tentative Late Cretaceous paleomagnetic pole for the area (long 167°E lat 76°N). The present study is an outgrowth of similar work on the Late Cretaceous Elkhorn Mountains Volcanics (Hanna, ms, 1967, 1973), which are the youngest rocks intruded by the Boulder batholith. Because the onset of plutonism overlapped with final episodes of volcanism (Hamilton and Myers, 1967; Robinson, Klepper, and Obradovich, 1968), the Boulder batholith results extend the volcanic rock results continuously in time. A total of 371 samples were obtained from 32 intrusive rock sites (fig. 1), 27 of which have been dated by the K-Ar method (Tilling, Klepper, and Obradovich, 1968).

This study was begun primarily to determine whether some rocks of the Boulder batholith possess reversed remanent magnetization, as do about 25 percent of rock units previously sampled in the Elkhorn Mountains Volcanics (Hanna, ms, 1967). Reversed polarities were discovered in 5 of the 20 plutons sampled. The occurrence of reversed polarities allows the possibility of (1) establishing a time sequence of field polarity

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for the Late Cretaceous interval spanning batholithic emplacement, (2) determining whether thermal remagnetization associated with igneous intrusion occurred extensively in the area, (3) correlating satellitic plutons of the batholith area with units in the batholith proper, where K-Ar ages and geologic relations do not permit a definite correlation, and (4) estimating more closely the time span of batholithic emplacement previously bracketed by Tilling, Klepper, and Obradovich (1968).

GEOLOGIC SETTING

The Boulder batholith is composed of at least 15 major plutons (Smedes, Klepper, and Tilling, 1968) which range in composition from gabbro to alaskite (Knopf, 1957) and crop out over an area of about 5500 km² in western Montana (fig. 1). The batholithic rocks intrude

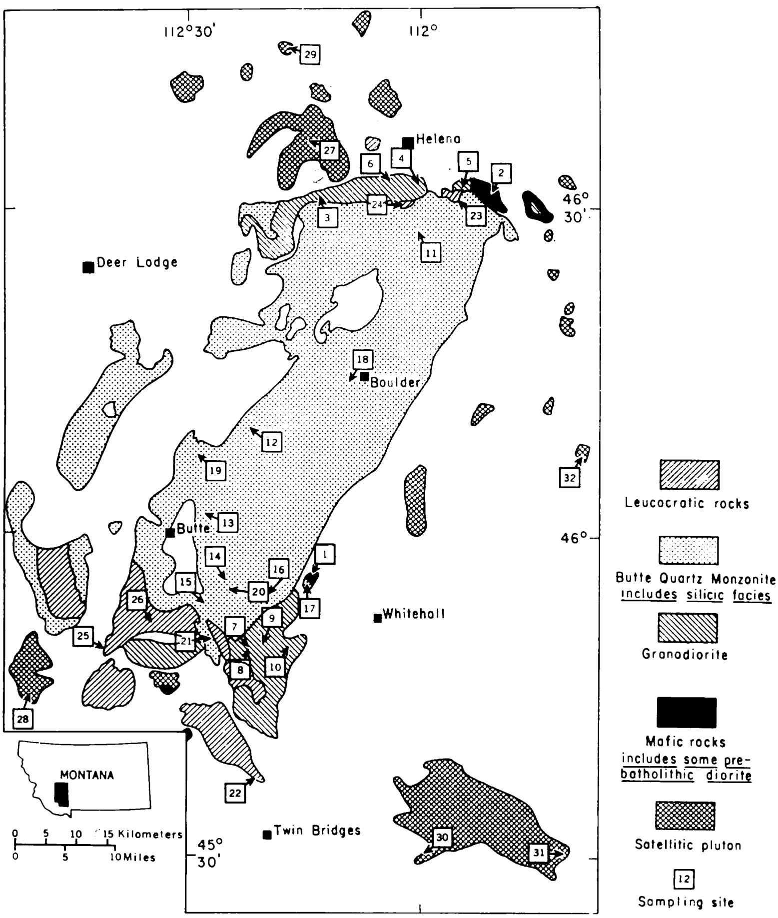

Fig. 1. Distribution of Late Cretaceous intrusive rocks of the Boulder batholith region. Sampling sites are marked by apexes of arrows, and numbers are keyed to rock units listed in table 1. Distribution of rocks generalized from Smedes, Klepper, and Tilling (1968).

rocks ranging in age from Precambrian to Late Cretaceous and are overlain locally by Tertiary and Quaternary sedimentary and volcanic rocks. Various parts of the batholith have been mapped or discussed by Weed (1899), Billingsley (1915), Robertson (1953), Knopf (1957), and by several geologists of the U.S. Geological Survey in projects largely coordinated by M. R. Klepper (Ruppel, 1961, 1963; Becraft and Pinckney, 1961; Pinckney and Becraft, 1961; Smedes, 1962, 1966, 1967, 1968; Klepper, 1962; Smedes and others, 1962; Becraft, Pinckney, and Rosenblum, 1963; Tilling, 1964; Prostka, 1966). For purposes of the present investigation, rocks of the Boulder batholith are grouped under headings used by Tilling, Klepper, and Obradovich (1968) in their analysis of K-Ar age data. These headings, in order of decreasing age, are: (1) mafic rocks, (2) granodiorite, (3) Butte Quartz Monzonite, (4) silicic facies of Butte Quartz Monzonite, and (5) leucocratic rocks.

Satellitic plutons also sampled (see fig. 1) include the "granodiorite, undivided" (site 27) of Knopf (1963), an unnamed pluton (site 28) shown on the map of Smedes, Klepper, and Tilling (1968), the Marysville stock (site 29) mapped by Barrell (1907) and Knopf (1950), the Tobacco Root batholith (sites 30 and 31) mapped in part by Tansley, Schafer, and Hart (1933), Reid (1957), Burger (ms), and Smith (1965, ms), and the Lone Mountain stock (site 32) mapped by Freeman, Ruppel, and Klepper (1958). These satellitic plutons cannot be fitted precisely into the intrusive sequence of the batholith proper because of the lack of definitive K-Ar age data and critical field relations. Correlations of these plutons with specific units of the Boulder batholith are attempted in the present study using rock magnetic data as a supporting tool.

One pre-batholithic intrusive, termed "diorite porphyry" by Prostka (1966, p. F11), is included in the analysis because K-Ar age data and field relations indicate that it was emplaced after extrusion of much of the Elkhorn Mountains Volcanics and therefore almost contemporaneously with the earliest phase of the Boulder batholith. The diorite porphyry intrudes the contact between the lower and middle members of the Elkhorn Mountains Volcanics which have an average K-Ar age of 78.0 ± 1.7 m.y. The diorite is intruded by mafic rocks of the Ringing Rocks stock (Prostka, 1966) having a K-Ar age of 78.2 ± 3.1 m.y. The diorite is similar in composition to the volcanic rocks it intrudes and is considered to have been emplaced ~78 m.y. ago.

FEATURES OF MAGNETIC MINERALS

The compositional transition of mafic older rocks to felsic younger ones making up the Boulder batholith correlates with a generally progressive decrease of iron oxide content (see table 1, column "Iron Oxide"). Mean values of petrographically determined iron oxide contents for the five main batholithic rock groups reflect this progression: (1) mafic rocks, 2.74 percent, (2) granodiorite, 2.17 percent, (3) Butte Quartz Monzonite 1.10 percent, (4) silicic facies of Butte Quartz Monzonite, 0.61 percent, and (5) leucocratic rocks, 1.02 percent. These mean iron-oxide contents are proportional to mean remanent magnetization intensities of the rock groups.[1] This relation suggests that much, if not most, of the remanent magnetization of these plutonic rocks is contained in the relatively large iron oxide grains of more than 100-μ diameter which are far more abundant than grains of 10μ or less.

Thermomagnetic data presented in table 1 indicate that the iron oxide in all rocks sampled has Curie points characteristic of nearly pure, titanium-poor magnetite. The thermomagnetic curves have single well-defined knees suggesting that most of the iron oxide is of uniform composition. A single exception is a sample of alaskite (table 1, site 19) which has a second feebly developed knee suggesting the presence of a secondary magnetic mineral having a Curie temperature of about 350°C.

Petrographic inspection of polished rock slabs under reflected light indicates that most rocks contain magnetite of uniform composition with little or no development of the ilmenite-hematite series. Rocks from only 8 of the 32 sites show distinct development of minor amounts of hematite or titanohematite, which is exhibited at grain margins near octahedral cleavage planes or, more rarely, as coarse lamellas within grains. This limited oxidation of magnetite is observed in samples from one site in granodiorite (site 10), two sites in the Butte Quartz Monzonite (sites 16 and 17), one site in silicic facies of the Butte Quartz Monzonite (site 19, which shows the double-knee thermomagnetic curve), one site in leucocratic rocks (site 24), and three sites in satellitic plutons (sites 27, 31, and 32).

In most rocks the magnetic grains are euhedral to subhedral and commonly tend to aggregate in clusters of ten or more. The large average grain size suggests that the natural remanent magnetization (NRM) will have low coercivities; in fact, these plutonic rocks are magnetically unstable, and many require magnetic cleaning to erase low-coercivity magnetization.

MEASUREMENT PROCEDURES

Remanent magnetizations were measured with spinner magnetometers of the types described by Doell and Cox (1965) and Phillips and Kuckes (1967). To remove secondary magnetization components, specimens were partly demagnetized in peak alternating fields of up to 400 oersteds, using equipment described by Doell and Cox (1967a). Thermomagnetic data for 30 specimens, measured in air, were obtained from a recording magnetic balance of Doell and Cox (1967b). Curie temperatures were estimated from plots of magnetization versus temperature in fields of 1500 to 5000 oersteds, using a linear heating rate of 10°C per minute within the temperature interval 30 to 700°C. The spinner magnetometers provided remanent magnetization directions accurate to

[1] The observed relationship between mean remanent magnetization intensity, J, and mean iron oxide content, Φ, for the rocks studied may be expressed with better than 20 percent accuracy by the equation

$$\log_{10} J = 0.42\Phi$$

where J is in units of 10^{-4} emu/cm^3 and Φ is in units of volume percent.

TABLE 1

Remanent magnetization and K-Ar age data for the Boulder batholith intrusive sequence (older to younger) established geologically

Rock Units Sampled	Site no. (map location)	Samples accepted N	Samples rejected	H_d, oe	D, deg	I, deg	J, 10^{-4} emu/cc	k
Pre-batholithic diorite porphyry*	1	8	2	50	172.7	69.9	6.08	11.8
Mafic rocks	2	7	0	50	269.8	79.2	14.6	23.9
Granodiorite**								
Unionville Granodiorite	3	6	0	400	46.2	42.9	1.14	23.6
	4	18	1	50	357.7	72.0	37.3	494.1
	5	8	0	100	1.8	76.4	3.65	86.7
	6	5	2	400	1.8	74.4	3.06	22.4
Rader Creek pluton	7	13	0	50	152.8	-67.4	4.49	34.4
	8	6	0	400	72.1	-63.0	1.27	15.1
	9	8	0	400	177.0	-58.5	1.06	2.1
	10	10	0	400	255.7	-82.4	1.79	13.4
Butte Quartz Monzonite (includes Clancy Granodiorite)								
	11	20	0	0	1.3	51.3	2.91	11.3
	12	10	0	0	44.2	73.0	11.6	33.7
	13	10	0	0	353.2	80.4	3.94	21.0
	14	12	1	0	359.2	72.2	2.05	6.1
	15	14	0	0	112.7	66.9	2.29	4.9
	16 ***	14	0	0	216.9	80.0	1.61	10.6
	17	7	0	0	305.0	65.1	2.62	148.8
Silicic facies of Butte Quartz Monzonite								
Pulpit Rock pluton	18	16	0	0	62.5	56.4	3.90	15.8
Alaskite	19	11	0	0	37.0	74.5	0.92	64.2
Homestake pluton	20	13	1	0	343.1	50.3	1.37	20.0
Leucocratic rocks**								
Donald pluton	21	15	2	0	223.6	76.3	3.83	32.9
Hell Canyon pluton	22	8	0	400	266.4	-75.2	0.89	5.7
Biotite granite	23	7	0	0	313.2	66.7	3.49	248.7
Biotite adamellite	24	9	0	50	325.2	69.4	1.48	14.8
Climax Gulch pluton	25	10	0	400	66.9	-25.7	108	7.0
	26	22	0	0	56.3	45.3	4.17	8.3
Satellitic plutons**								
	27	10	0	0	352.0	57.8	3.18	32.6
	28	13	2	400	44.8	-17.6	0.85	13.3
Marysville stock	29	17	5	0	336.8	79.4	6.49	17.7
Tobacco Root batholith	30	21	0	400	201.1	-59.9	4.03	116.4
	31	11	4	400	228.4	-36.3	0.71	6.6
Lone Mountain stock	32	12	0	100	14.9	80.3	1.21	30.1

and associated intrusive rocks. Rock units are listed in order of (Tilling and others, 1968)

α_{95} deg	ε, deg	Pol	Demagnetization Properties $J_0/J_{50}/J_{400}$	$\delta_0/\delta_{50}/\delta_{400}$	IRON OXIDE, VOLUME %	T_c, °C	K-Ar Min	K-Ar Age, m.y.	Age Source	Tilling et al. (1968) locality
16.8	23.9	N	6/40/3.47/1	0.66/0.57/1	3.50	580		~78.0	1	
12.6	16.6	N	6.26/3.47/1	1.07/0.45/1	2.74	580	B	75.8 ± 3.8	2	7
							B	77.4 ± 3.1	1	
14.1	16.8	N	14.6/n.d./1	2.38/n.d./1	1.98	565	B	76.4	3	3
1.6	3.6	N	1.06/1/n.d.	1.58/ 1 / n.d.	1.97	575	B	77.8	3	5
6.0	8.7	N	2.48/1.09/1	1.20/0.64/1	2.26	575	B	72.4	6	6
16.5	17.2	N	7.03/2.74/1	2.81/2.16/1	1.82	575		n.d		none
7.2	13.9	R	1.21/1.53/1	2.58/0.54/1	2.49	580	B	76.7 ± 3.1	8	22
							H	76.7 ± 3.1	8	
17.8	21.0	R	9.80/n.d./1	2.07/n.d./1	1.74	575		n.d.		none
52.3	59.3	R	3.42/n.d./1	0.32/n.d./1	2.79	580	B	72.8 ± 3.6	2	23
13.7	22.3	R	16.6/n.d./1	1.41/n.d./1	2.31	580	B	73.9 ± 3.7	2	24
							H	74.7 ± 3.0	1	
10.2	24.4	N	2.85/1.24/1	0.29/0.58/1	0.78	580	B	82.1	4	10a
							B	81.4	5	
							B	73.2	3	
							H	76.0	5	
							B	71.7 ± 2.3	1	10b
							B	71.9 ± 2.2	1	
							H	73.3 ± 2.5	1	
							H	71.4 ± 2.5	1	
8.4	14.0	N	2.18/1.95/1	0.87/0.99/1	0.78	575	B	75.8 ± 3.0	8	12
							B	73.1 ± 2.9	8	
							H	81.5 ± 3.3	8	
10.8	17.8	N	2.88/1.99/1	0.45/0.45/1	1.22	580	B	75.1 ± 3.0	8	14
							H	75.0 ± 3.0	8	
19.2	33.5	N	1.58/1.07/1	0.40/0.68/1	1.79	580	B	72.9 ± 3.6	2	16
							H	71.2 ± 3.6	1	
20.1	37.6	N	1.99/n.d./1	0.48/n.d./1	1.25	580	B	70.4 ± 2.8	8	18a
							B	70.3 ± 2.8	8	
							H	80.4 ± 3.2	8	
							H	78.2 ± 3.1	8	
							B	72.7 ± 3.0	1	18b
							H	76.5 ± 2.4	1	
							H	75.0 ± 3.4	1	
12.8	25.3	N	1.39/1.11/1	0.76/1.13/1	0.68	575		n.d.		none
5.0	6.5	N	3.96/n.d./1	0.86/n.d./1	1.18	580		n.d.		none
9.6	20.6	N	2.80/0.86/1	0.27/0.80/1	1.17	580	B	71.9 ± 3.6	2	11
							B	70.2 ± 3.5	2	
5.7	10.1	N	2.70/2.24/1	0.35/0.35/1	0.46	575	B	75.1 ± 3.7	2	13
9.5	18.2	N	1.98/n.d./1	0.46/n.d./1	0.21	575	B	70.5 ± 3.5	2	17
							B	71.7 ± 3.3	1	
							H	74.7 ± 2.6	1	
6.8	14.2	N	3.86/n.d./1	0.28/n.d./1	1.00	580	B	70.2 ± 3.5	2	21
							B	74.0 ± 3.0	1	
							H	73.2 ± 2.5	1	
25.4	34.4	R	5.57/n.d./1	0.60/n.d./1	1.09	580	B	70.1 ± 3.5	2	26
							H	73.9 ± 3.0	1	
3.8	5.1	N	4.92/3.30/1	0.19/0.31/1	0.89	575	B	73.5	3	4
13.8	21.3	N	2.68/1.67/1	0.46/0.42/1	0.66	570	B	70.2	3	8
19.7	31.1	R	1.40/n.d./1	1.05/n.d/1	1.28	n.d.	B	68.0 ± 2.7	8	19
							H	69.0 ± 2.8	8	
11.5	28.8	N	0.33/n.d./1	0.34/n.d./1	1.21	580	B	70.6 ± 3.5	2	20
8.6	14.3	N	3.28/2.45/1	0.28/0.30/1	1.49	580	B	73.0 ± 2.9	8	2
							B	71.2 ± 2.8	8	
11.8	22.4	R	3.10/n.d./1	0.96/n.d./1	2.37	570	B	77.1 ± 3.1	8	25
							H	77.2 ± 3.1	8	
8.7	19.4	N	6.90/5.84/1	0.26/0.30/1	1.42	575	B	78.0	7	1
3.0	7.5	R	5.24/2.83/1	8.79/9.48/1	1.40	n.d.	B	75	9	none
19.2	32.0	R	3.68/2.25/1	1.06/1.44/1	1.50	575	B	52?****	9	none
8.0	14.8	N	6.78/2.88/1	0.27/0.27/1	1.87	580		n.d.		none

Explanation overleaf

within about 2° and magnetization intensities to within about 5 percent. The temperature calibration for the magnetic balance has an estimated accuracy of 2°C.

Generally, one, two, or three specimens were prepared from oriented cored samples using portable field equipment described by Doell and Cox (1965). Remanent magnetizations of specimens were averaged for each sample, and the directional data for samples were conventionally

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Explanation for table 1 (p. 782-783)

N: Number of samples consisting of one, two, or three specimens used in statistical analysis. Rejected samples have highly anomalous magnetization directions.
H_d: Peak demagnetization field, oersteds.
D: Declination of remanent magnetization, degrees east of north.
I: Inclination of remanent magnetization, degrees below horizontal.
J: Mean remanent magnetization intensity, 10^{-4} emu/cm^3.
k: Between-sample precision parameter estimate (Fisher, 1953).
a_{95}: 95% confidence angle about the estimated mean direction, degrees.
δ: Angular standard deviation (Wilson, 1959).
Pol: Polarity of remanent magnetization, N normal, R reversed.
$J_0/J_{50}/J_{400}$: Ratios of mean remanent magnetization intensities after partial demagnetization in fields of 0, 50, and 400 oersteds, normalized so that $J_{400} = 1$.
$\delta_0/\delta_{50}/\delta_{400}$: Ratios of angular standard deviations after partial demagnetization in fields of 0, 50, 400 oersteds, normalized so that $\delta_{400} = 1$.
T_c: Curie temperature, degrees Centigrade.
K-Ar min: Mineral used in K-Ar dating: B = biotite, H = hornblende.

Age sources:
1. J. D. Obradovich, U.S. Geol. Survey, Denver, Colorado, *in* Tilling, Klepper, and Obradovich (1968).
2. R. F. Marvin and H. H. Thomas, U.S. Geol. Survey, Washington, D.C., *in* Tilling, Klepper, and Obradovich (1968).
3. Geochron Lab., Inc., *in* Knopf (1964).
4. R. E. Folinsbee *in* Knopf (1964).
5. J. F. Evernden *in* Knopf (1964).
6. Geochron (Knopf, written commun., 1964), *in* Tilling, Klepper, and Obradovich (1963).
7. Baadsgaard, Folinsbee, and Lipson (1961).
8. McDowell, Lamont Observatory, 1966, *in* Tilling, Klepper, and Obradovich (1968).
9. Giletti (1966, 1968).

n.d.: not determined

* "Diorite porphyry" of Prostka (1966, p. F11), which intrudes Elkhorn Mountains Volcanics having a K-Ar age of 78 ± 1.7 m.y., and which is intruded by mafic rocks of the Ringing Rocks stock having a K-Ar age of 78.2 ± 3.1 m.y.

** Intrusive sequence within group not established geologically because of separated occurrences (Tilling, Klepper, and Obradovich, 1968).

*** Quartz monzonite of the Easter Lily stock (Prostka, 1966, p. F16), which is here grouped with sites in the Butte Quartz Monzonite, the main mass of which crops out 1 km to the west.

**** Validity of date uncertain (Giletti, 1966).

Age determination constants: $\lambda_\beta = 4.72 \times 10^{-10}$ YR^{-1}; $\lambda_\epsilon = 1.19 \times 10^{-10}$ YR^{-1}

treated using Fisher's (1953) statistics for dispersion on a sphere. It was necessary to restrict sampling to the freshest parts of outcrops, which in many places required drilling cores less than 1 m apart. An initial sampling program that involved drilling at equally spaced intervals several meters apart failed because local weathering and slumping of outcrops produced ambiguous data. After preliminary data had been inspected, 13 collecting sites required resampling. The statistical analysis of the NRM directions from a given site does not average a time variation of the ambient Late Cretaceous magnetic field, as it sometimes does in a stratigraphic sampling of volcanic rocks, but instead it averages errors in the collection and preparation of samples as well as real differences in magnetization, usually of unknown origin, between cores.

REMANENT MAGNETIZATION DATA

Remanent magnetization and K-Ar age data are listed in table 1 in order of intrusive sequence determined by field relations (Tilling, Klepper, and Obradovich, 1968). Rocks at 23 sites are normally polarized (same sense as the present Earth's field) after magnetic cleaning, and rocks at 9 sites are reversely polarized. Only four of the nine reversely polarized rock sites (7, 8, 25, and 30) had reversed magnetizations prior to demagnetization; all others had normally polarized magnetizations. Reversed magnetization was usually discovered only after application of 400-oersted demagnetizing fields (see fig. 2).

Remanent magnetization directions at most sites, whether normal or reversed, show considerable dispersion; mean directions at 21 sites have precision parameter estimates (see table 1, column "k") of less than 25, and only 4 have estimates of over 100. Ratios of angular standard deviation (Wilson, 1959) at demagnetizing fields of 0[2], 50, and 400 oersteds (see table 1, column "$\delta_0/\delta_{50}/\delta_{400}$") show that dispersion was minimal at 0 oersteds for rocks at 18 sites, at 50 oersteds for rocks at 7 sites, and at 400 oersteds for rocks at 7 sites. The selection of the optimal demagnetizing field for each site was based on minimum dispersion of directions except for three sites (9, 22, and 28) having rocks with reversed magnetization after 400-oersted demagnetization. In general, demagnetization tends to reduce dispersion within mafic rocks and granodiorite and tends to increase dispersion within the Butte Quartz Monzonite and leucocratic rocks. Demagnetization in fields above 400 oersteds was not routinely attempted because many rocks responded unstably to high fields and because dispersion ordinarily increased as a result of high-field application.

Plots of magnetization intensity versus demagnetizing field (not shown) made for test specimens from each site for field values of 25, 50, 100, 150, 200, and 400 oersteds are curves characteristic of thermoremanent or chemical remanent magnetization. A thermoremanent origin is tentatively assumed because of the general absence of oxidation in magnetic mineral grains and the general agreement of magnetization polarities

[2] A 0-oersted magnetization is used here to denote the originally measured NRM.

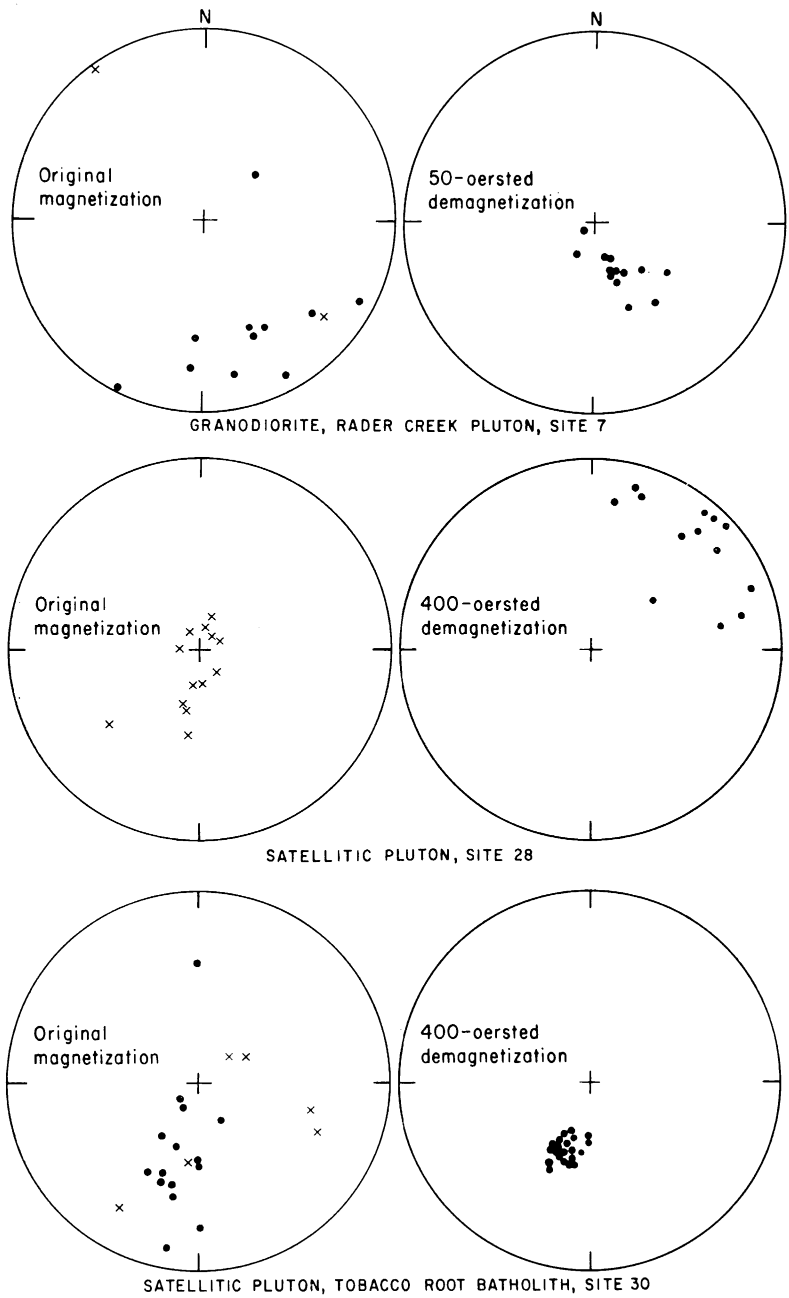

Fig. 2. Remanent magnetization directions before and after partial demagnetization of samples from three reversely magnetized sites (see fig. 1 for locations). Lambert equal- area projection. x, north-seeking direction on lower hemisphere; closed circle, north-seeking direction on upper hemisphere.

among widely separated sites within single plutons (note exception for sites 25 and 26).

Mean remanent magnetization directions for most sites (called "site mean directions", fig. 3) have steep inclinations characteristic of most site mean directions in the Elkhorn Mountains Volcanics (Hanna, 1967). Notable exceptions are directions for sites 3, 25, 26, 28, and 31 which have inclinations of 45° or less. The anomalous direction of site 3 may reflect primary thermoremanent magnetization (TRM) acqured during a brief excursion of the paleomagnetic field while the Unionville Granodiorite cooled. Alternatively, the anomalous direction may reflect secondary magnetization acquired during a rapid field excursion while the rocks were reheated by the Clancy Granodiorite (equivalent to the Butte Quartz Monzonite according to Tilling, Klepper, and Obradovich, 1968) near the contact of the two bodies. However, the anomalous inclinations of sites 25, 26, 28, and 31 cannot be explained by remagnetization during a reheating process.

INTERPRETATION

Did reheating affect magnetizations?—Because a large amount of heat was associated with intrusion of the Butte Quartz Monzonite body, which makes up 75 percent of the exposed Boulder batholith, the possible influence of this heat on magnetizations internal and external to the intrusive body cannot be ignored. Two salient points are: (1) the TRM of the intrusive body may have been acquired over a long period of time during the cooling process while the Curie temperature isotherms progressed from the outside edge of the body inward, resulting in a time record of magnetization directions within the intruding body reflecting short-term changes in paleomagnetic field direction. (2) Heating of the surrounding rocks may have been sufficient to remagnetize the intruded rocks thermally by allowing addition of either a partial thermoremanent magnetization (PTRM) or a chemical remanent magnetization (CRM).

The first effect, which has been studied for rocks elsewhere by Jaeger and Green (1956) and Clark (1969), cannot be convincingly demonstrated here because sites within the Butte Quartz Monzonite are not evenly distributed across the body. Although the few sites (11, 13, 14, 18 and 20) that are more than 5 km inside the outer margin of the Butte Quartz Monzonite have mean directions that are collectively a few degrees away from those of sites closer to the margin (fig. 3), the associated confidence circles (see table 1, α_{95} column) indicate that they are not significantly different at the 95-percent level of confidence. It seems likely that the field was nearly constant in direction during the cooling period of the Butte Quartz Monzonite.

The second effect may be tested in part by noting whether magnetizations of surroundings rocks are parallel to magnetizations of the Butte Quartz Monzonite, by determining the Curie temperatures and magnetic responses to demagnetizing fields for surrounding rocks and

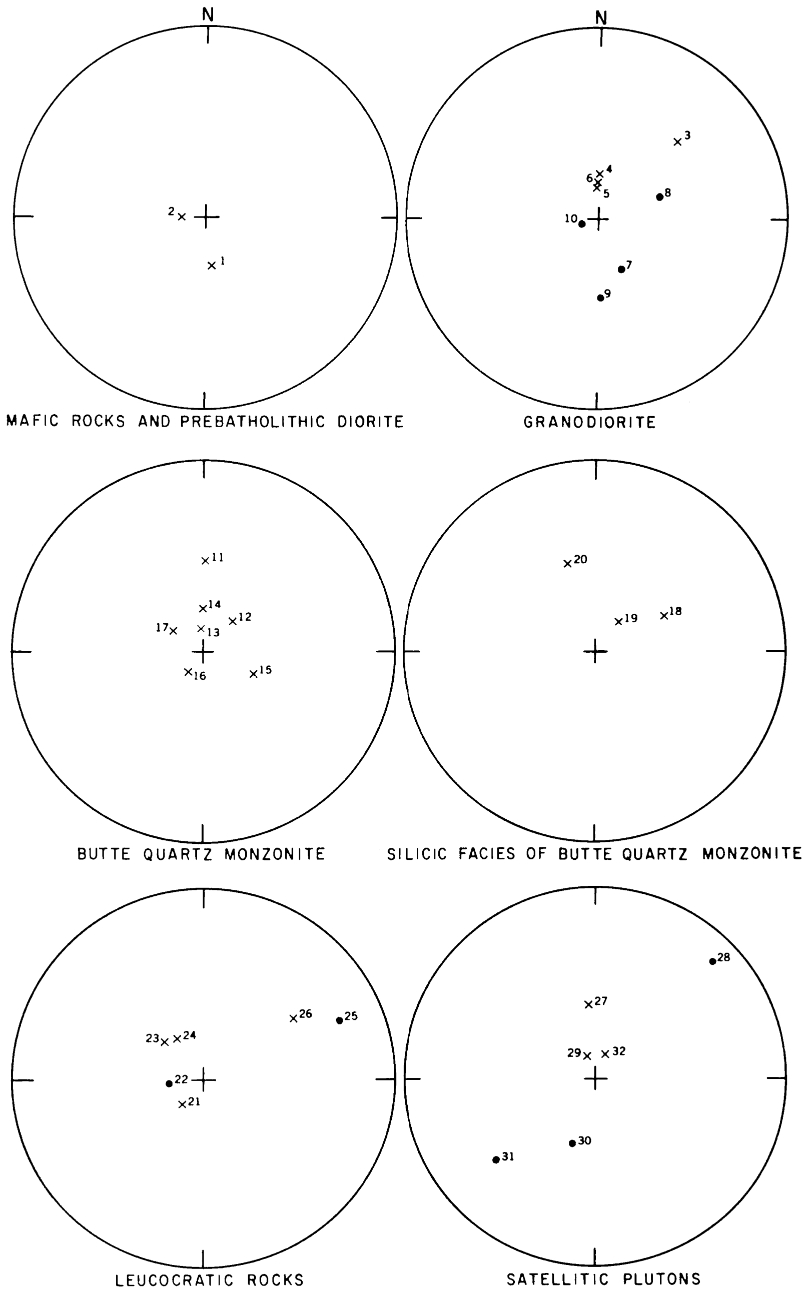

Fig. 3. Site mean directions of intrusive rocks of the Boulder batholith region. Lambert equal-area projection. x, north-seeking direction on lower hemisphere; closed circle, north-seeking direction on upper hemisphere. Site numbers are keyed to figure 1 and table 1.

by searching for evidence of oxidation or other chemical changes in magnetic minerals contained in the intruded rocks. Because a.f. demagnetization generally reduced the dispersion of magnetization directions of intruded rocks but increased the dispersion of directions of Butte Quartz Monzonite (see table 1, $\delta_0/\delta_{50}/\delta_{40}$ column), we may infer that the intruded rocks contain random secondary magnetization having coercivities less than the peak demagnetizing field of 400 oersteds. However, this random magnetization would not result from reheating by the Butte Quartz Monzonite if the paleomagnetic field was nearly constant during cooling of the intrusive body, as inferred above. The cause of the differences in amounts of random secondary magnetization between the intruded and intrusive rocks is unknown.

Intruded rocks in the northern part of the area, including mafic rocks and Unionville Granodiorite, have high-coercivity magnetizations (after 400-oersted demagnetization) which are similar in direction and polarity to those of the Butte Quartz Monzonite, except for the shallow inclination of site 3. These magnetizations may consist of primary TRM, secondary PTRM or CRM, or some combination of these. Intruded rocks in the southern part of the area, including granodiorite of the Rader Creek pluton, have high-coercivity magnetizations which are opposite to those of the Butte Quartz Monzonite, indicating that the hard magnetization is primary TRM. The lack of evidence for oxidation of magnetite and the high Curie temperatures of the intruded rocks suggest that CRM and PTRM are not present in appreciable amounts in either the northern or southern parts of the area. Thus the magnetizations that remain in partially demagnetized mafic rocks and Unionville Granodiorite (including site 3) are inferred to consist of primary TRM rather than secondary PTRM or CRM introduced during a reheating period.

Granodiorite from two sites (9 and 10) in the Rader Creek pluton have original magnetization directions within 20° of the present field direction in western Montana. The soft secondary magnetizations of these rocks are systematic and may consist of low-temperature VRM or small amounts of moderate-temperature PTRM. If reheating contributed to the secondary magnetization, the effect was insufficient to persist after the a.f. cleaning process.

Thermal remagnetization by smaller intrusive bodies appears to have been minimal, if not negligible, at the few sites of intruded rocks relatively close to the intrusion margin. For example, it might be postulated that reversely polarized leucocratic rocks of the Hell Canyon pluton (site 22) thermally remagnetized reversely polarized granodiorite of the adjacent Rader Creek pluton (sites 7, 8, 9, and 10) during a reversed magnetic field epoch. However, this possibly is greatly lessened by the occurrence of normally polarized leucocratic rocks of the Donald pluton (site 21) which intrude the reversely magnetized Rader Creek pluton. We conclude that remagnetization of intruded rocks due to reheating of these rocks by the Butte Quartz Monzonite or smaller plutons has been insufficient to affect paleomagnetic results adversely.

Characteristics of field during batholithic emplacement.—The late Cretaceous field in western Montana during batholithoic emplacement was characterized by periods of steep inclination, shallow inclination, and occasional polarity reversal. The field was steeply inclined for periods during intrusion of each of the main groups of rocks (fig. 3) but was shallowly inclined during intrusion of some leucocratic rocks (sites 25 and 26), satellitic plutons (sites 28 and 31), and possibly one site of Unionville Granodiorite (site 3). As previously noted, the low inclination of site 3 may represent a secondary magnetization component acquired by granodiorite consequent to reheating by a nearby intrusive body; however, a primary magnetization has been tentatively inferred. Field polarities were exclusively normal during intrusion of mafic rocks and Butte Quartz Monzonite (including the silicic facies) but were both normal and reversed during intrusion of granodiorite, leucocratic rocks, and satellitic plutons.

Nature of low-inclination fields.—Steep field inclinations of greater than 45° are characteristic of the Late Cretaceous of North America above lat 30°N (see, for example, Larochelle, 1968) and are far more abundant than low inclinations in sampled rocks of the Elkhorn Mountains Volcanics and Boulder batholith. The anomalous low inclinations corresponding to leucocratic rock sites 25 and 26, satelite pluton sites 28 and 31, and Unionville Granodiorite site 3 in the Boulder batholith region are similar to data on Cretaceous rocks from the Franciscan Formation of California (Grommé and Glukoster, 1965; Saad, 1969), from a single unit in the Elkhorn Mountains Volcanics of Montana (Hanna, 1969, 1973), and from dikes in Jamaica (Watkins and Cambray, 1971).

The northeastward bias of low-inclination Cretaceous directions in California, emphasized by Saad (1969), is also apparent in low-inclination directions in Montana. Although the origin of these anomalous directions is still in doubt, the Boulder batholith data suggest their possible duration of phases. For example, the reversed and normal low-inclination directions of sites 25 and 26, representing distinct phases of Climax Gulch leucocratic rocks according to K-Ar and petrochemical data (R. I. Tilling, 1972, written commun.), suggest that anomalous directions may have persisted within a region confined to several tens of degrees for a period of as much as 1.5 m.y. Other evidence, such as K-Ar age brackets around satellitic pluton site 28, having a northeast low-inclination direction, suggest that anomalous directions may have persisted no longer than a fraction of a million years, although the anomaly may have persisted much longer than the magnetization time of the pluton. The remarkable low-inclination direction of satellitic pluton site 31, biased toward the southwest, appears to be the reversed polarity of a shallowly inclined, northeastward field direction. The few data suggest that some low-inclination fields (sites 25 and 26) may reflect main dipole movement to a relatively stable position where subsequent polarity reversal occurred, whereas others (site 28 and possibly site 3) represent more rapid field excursions which might have occurred during reversal.

Boulder batholith pole position.—A summary of mean remanent magnetizations and K-Ar ages (table 2 and fig. 4) for the main groups of rocks shows that the streaked distribution of batholith directions lies to the north at high inclination from the single direction for pre-batholithic diorite, indicating differences in paleomagnetic field direction during various times of cooling. Satellitic plutons are excluded as a group because they have significantly different K-Ar ages and undoubtedly were intruded throughout the time span of batholithic emplacement. Apart from the difference between the pre-batholithic and batholith directions, it is not possible to infer a systematic time sequence of field migration from the data. Nor is it possible to extract secular variation information from the data, mainly because the scatter of directions is too great, and the K-Ar data insufficiently precise for such a detailed analysis, even though the observed dispersion may be partly caused by secular variation.

Because the mean directions for the main groups of rocks were obtained from highly variable numbers of samples (table 2, $N = 1$ to $N = 8$), they have not been used to compute a paleomagnetic pole. Rather, the set of all site mean directions, excluding pre-batholithic diorite site 1 and the anomalous low-inclination sites 25, 26, 28, and 31, are given equal weight for computation of the pole. Low-inclination site 3 has been tentatively grouped with other Unionville Granodiorite sites that have nearly the same K-Ar age. The 27 sites have a mean magnetization direction of $D = 0.8°$ and $I = 76.0°$, about 19° from the direction previously obtained for the Elkhorn Mountains Volcanics, and they correspond to a virtual geomagnetic pole of long 111.0 W and lat 72.7N°, about 11° from the computed pole for the Elkhorn Mountains Volcanics. The oval of confidence associated with the Boulder batholith pole ($\delta p = 11.8°$, $\delta m = 12.8°$) indicates that this pole is not significantly different from the Elkhorn Mountains Volcanics pole at the 95 percent level of confidence. The computed Boulder batholith pole may be used to replace the one (167°E, 76°N) previously obtained from reconnaissance data of Colville (ms) based on 15 samples of Butte Quartz Monzonite.

Geographic separation of polarities.—A remarkable feature of the map distribution of site polarities (fig. 4) is the northerly concentration of normal polarities and the southerly concentration of reversed ones, the dividing line conveniently expressed by an east-west line at lat 45°50′N. In the absence of detailed geologic mapping and K-Ar dating, the paleomagnetic data might suggest only two intrusive episodes, one during a normal field epoch and the other during a reversed field epoch. Alternatively, the data might suggest that the northerly or southerly regions were regionally remagnetized after intrusion, perhaps as a result of reheating or as an indirect response to major tectonism. Neither of these interpretations, however, is tenable in light of available geologic and K-Ar data.

TABLE 2

Mean K-Ar ages and remanent magnetizations for the main groups of Boulder batholith rocks, arranged younger to older, excluding satellitic plutons. Virtual geomagnetic poles of Late Cretaceous igneous rocks are included.

	K-Ar Age Data*		Remanent Magnetization Data**					
	Range (m.y.)	Mean (m.y.)	N	D (deg)	I (deg)	J (10^{-4} emu/cm^3)		Polarity
Boulder batholith								
Leucocratic rocks	68.0 - 73.9	71.3 ± 1.6	6	304.5	81.0	2.42***		N,R
Silicic facies of Butte Quartz Monzonite	70.2 - 75.1	72.4 ± 2.2	3	023.3	62.5	2.06		N
Butte Quartz Monzonite	70.3 - 76.5	73.2 ± 1.0	7	004.9	79.0	3.86		N
Granodiorite	72.4 - 77.8	75.2 ± 1.7	8	000.7	74.0	6.72		N,R
Mafic rocks	73.6 - 78.2	76.2 ± 3.1	1	269.8	79.2	14.6		N
Pre-batholithic diorite		~78.0	1	172.7	69.9	6.08		N
				Virtual Geomagnetic Pole				
				Long.(deg)	Lat.(deg)	Δp	Δm	
Boulder batholith, all rocks ∓	68 - 78	73	27	111°W	73°N	12	13	N,R
Elkhorn Mountains Volcanics ∓	77.6 - 78.2	78.0 ± 1.7	13	171°W	69°N	7	10	N,R

*From table 4 of Tilling, Klepper, and Obradovich (1968, p. 686), Error of the mean given at the 95% confidence level and calculated using Students "t" factor for limited sample population. Age of pre-batholithic diorite is estimated, as explained in text.

**Reversed polarities were transposed to antipodal positions prior to calculation of mean values.

***Anomously high magnetization intensity of site 25 has not been used in calculation of mean value.

∓Complete compilation parameters in format used by Irving (1964):

Boulder batholith, all rocks: D=001°; I=76.0°; k=17; α_{95}=7° [Excludes data of sites 1, 25, 26, 28, and 31].
Elkhorn Mountains Volcanics: D=329°; I=69.5,; k=60; α_{95}=5° [From Hanna (1967)].

N: Number of mean site directions used in estimating mean direction.

δp,δm: Semiaxes of the 95% confidence oval associated with the Virtual Geomagnetic Pole (Cox and Doell, 1960).

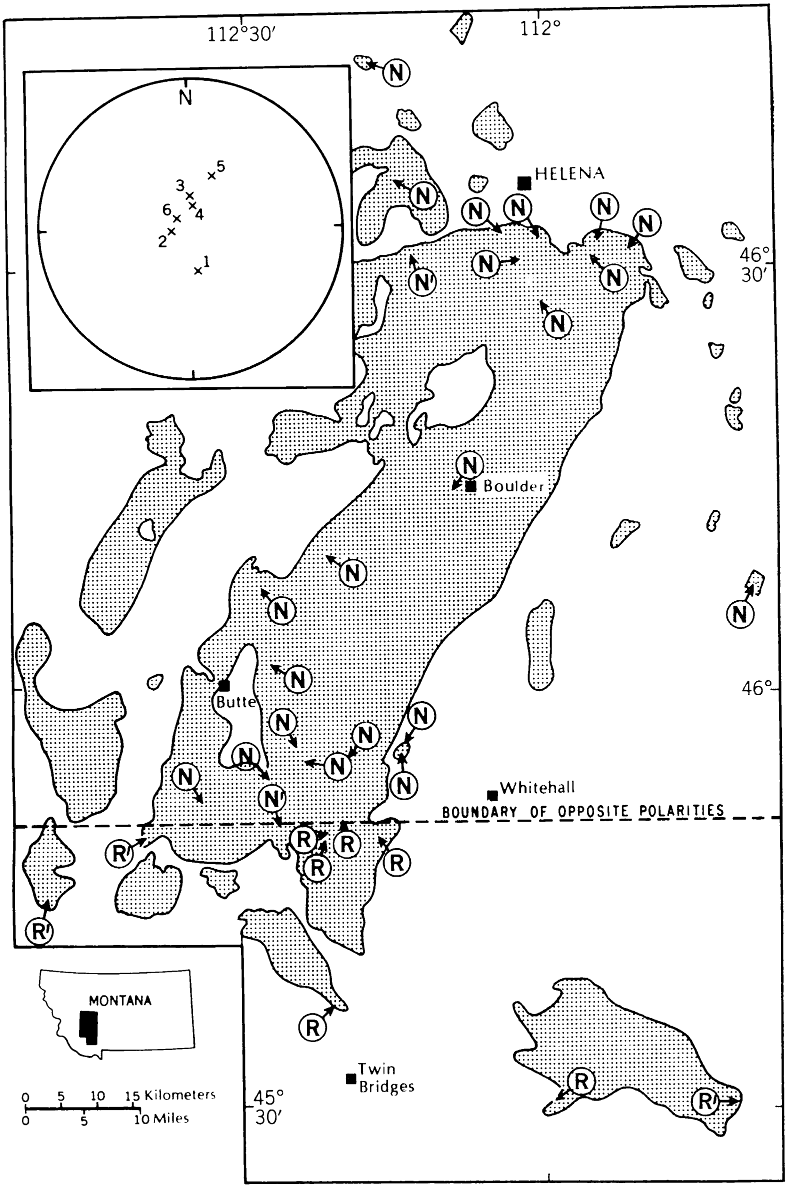

Fig. 4. Map showing remanent magnetization polarities (N, normal; R, reversed) for sampling sites of figure 1 and Lambert equal-area projection of mean north-seeking directions for rock groups of table 1. Darkened map areas are undivided Late Cretaceous intrusive rocks. East-west dashed line separates area into a northern region of normal polarities and a southern region of reversed polarities. 1, prebatholithic diorite; 2, mafic rocks; 3, granodiorite; 4, Butte Quartz Monzonite; 5, silicic facies of Butte Quartz Monzonite; 6, leucocratic rocks.

The geographic separation of polarities also suggests a possible relation to Pb and Sr isotope data (Doe and others, 1968) and chemical data (R. I. Tilling, 1972, written commun.), which indicate that the southernmost plutons of the batholith region were derived from a magmatic source different from that for the rest of the batholith. These southern plutons have reversed polarities, with the exceptions of Donald pluton leucocratic rock site 21 and Climax Gulch leucocratic rock site 26, and no other plutons studied in the batholith area have these polarities. However, even if the exceptions of sites 21 and 26 are ignored, it is difficult to support a correlation between magnetization polarity and plutonic rock source on the basis of observed iron oxide mineralogy. A possible correlation of self-reversed magnetization with the southerly group of rocks has been considered because special assemblages of iron oxides are known occasionally to undergo self-reversals. A remarkable example of self-reversed magnetization occurs in quartz diorite from the Bucks batholith in northern California, which contains a mixture of self-reversed ilmenohematite and normally polarized magnetite (Merrill and Grommé, 1969). In the present investigation, however, systematic differences in iron oxide assemblages between the northerly and southerly groups of rocks have not been detected.

Because the relation between polarity and rock series cannot be explained on the basis of self-reversed magnetization associated with characteristic iron oxide assemblages and because a single self-reversed mechanism appears unlikely to have operated within a variety of rock types having different ages, the map separation of polarities is tentatively assumed to be fortuitous. Futhermore, no claim can be made that the geographic separation of polarities is as yet precisely established because no attempt was made to sample systematically over a large area at a uniform interval. That normally polarized plutonic rocks, in addition to those of sites 21 and 26, occur south of the polarity boundary is suggested by data of Colville (ms) and Milford J. Benham (1961, oral commun.) from the Tobacco Root batholith satellitic pluton and associated intrusive rocks. However, because these reconnaissance samples were not subjected to partial demagnetization, uncertainties about stability and primary magnetization polarity remain.

Correlation of intrusives using polarities.—Field relations and K-Ar data suggest that the reversed magnetization polarities represent four distinct periods of field reversal, having ages of about 68.5, 72, 75, and 77 m.y. The most recent reversal period is recorded by site 25, which probably represents an intrusive phase of Climax Gulch pluton leucocratic rocks distinctly later than the normally polarized phase of site 26. The 72-m.y. reversal, represented by Hell Canyon pluton leucocratic rocks (site 22), may have been a relatively short-lived event because the normally polarized rocks elsewhere in the batholith have dates slightly younger and older than 72 m.y. Although the K-Ar data for these leucocratic rock sites have uncertainties sufficiently great to allow the possibility of mutual correlation, they are considered distinct, partly because their mean directions differ greatly in inclination (table 1, fig. 3). The 75-m.y. reversal is recorded by both granodiorite of the Rader Creek pluton (sites 7, 8, 9, and 10) and quartz monzonite of a pluton in the satellitic Tobacco Root batholith (site 30). The 77-m.y. reversal is inferred from the low-inclination direction of satellitic pluton site 28 and may coincide with one of the several reversals reported previously for the Elkhorn Mountains Volcanics.

On the basis of magnetization polarities, the most important conclusion pertaining to correlation is that the Unionville Granodiorite and granodiorite of the Rader Creek pluton were emplaced and cooled at distinctly different times in fields of opposite polarity. Formerly, these two granodiorites were considered contemporaneous and were combined (Tilling, Klepper, and Obradovich, 1968) into a single batholitic rock group on the basis of overlapping K-Ar data. Reanalysis of the K-Ar data, given the fact that the two granodiorites formed at distinctly different times, indicates that the Unionville Granodiorite may be about half a million years older than granodiorite of the Rader Creek pluton.

Just as K-Ar ages have been used to refine the inferred sequence of intrusion based on field relations (Tilling, Klepper, and Obradovich, 1968), directions and polarities of magnetization may be used to refine the sequence based on field relations and K-Ar ages. This refinement results from restrictions placed on the lumping of rock groups that seem similar or identical on the basis of field relations or K-Ar ages but that must have cooled at distinctly different times on the basis of magnetizations. If magnetizations are used to help determine the appropriate lumping of rock groups, more representative averages of K-Ar dates may be determined, thereby improving the inferred sequence.

For example, as noted above, the Unionville Granodiorite and granodiorite of the Rader Creek pluton are magnetically different although field relations and K-Ar ages do not show a definite difference between them in the intrusive sequence. Given the magnetization differences, the K-Ar ages of each of the two groups of granodiorites may be averaged separately and placed separately within the intrusive sequence (table 3). Likewise, plutons of leucocratic rocks and satellitic plutons, which have separated occurrences and overlapping K-Ar ages, may be more definitely placed within the sequence using magnetization polarities. Among leucocratic rocks, two units that have been grouped on the basis of similar magnetizations are biotite granite (site 23) and adamellite (site 24) whereas two that have been kept distinct are the reversed and normal phases of the Climax Gulch pluton (sites 25 and 26). Among satellitic plutons, the pluton of site 27 must be considered distinct from the Hell Creek pluton (site 22) because of their opposite magnetization polarities, although the two plutons have almost identical K-Ar ages.

If the restrictions placed on the lumping or separation of rock groups for obtaining average K-Ar ages are valid, the resulting refinement of the intrusive sequence (table 3) suggests that batholith emplace-

TABLE 3

Refined interpretation of intrusive sequence in the Boulder batholith, based on magnetization, K-Ar, and field data.

Igneous Rock Unit	Fig. 5 label	Site No.	K-Ar Data N	K-Ar Data K-Ar date ± s.d.* m.y.	Remanent Magnetization Data N	D deg	I deg	Polarity**
Boulder batholith and related rocks								
Leucocratic rocks								
Climax Gulch pluton, reversed phase	A	25	2	68.5 ± 0.7	1	66.9	-25.7	R'
normal phase	B	26	1	70.6 ± 3.5	1	56.3	45.3	N'
Biotite granite and ademellite	C	23,24	2	71.8 ± 2.3	2	318.8	68.2	N
Hell Canyon pluton	D	22	2	72.0 ± 2.7	1	266.4	-75.2	R
Satellitic pluton, site 27	E	27	2	72.1 ± 1.3	1	352.0	57.8	N
Leucocratic rocks								
Donald pluton	F	21	3	72.5 ± 2.0	1	223.6	76.3	N
Butte Quartz Monzonite, including silicic facies	G	11-20	23	73.0 ± 2.0	10	13.8	75.1	N
Satellitic pluton, site 30	H	30	1	75	1	201.1	-59.9	R
Granodiorite of Rader Creek pluton	I	7-10	5	75.0 ± 1.7	4	146.2	-76.0	R
Unionville Granodiorite	J	3-6	3	75.5 ± 2.8	4	22.0	68.2	N
Mafic rocks	K	2	2	76.6 ± 1.1	1	269.8	79.2	N
Satellitic pluton, site 28	L	28	2	77.2 ± 0.1	1	44.8	-17.6	R'
29	M	29	1	78.0	1	336.8	79.4	N
Prebatholithic diorite	N	1	1	~78***	1	172.7	69.9	N
Elkhorn Mountains Volcanics			3	78.0 ± 1.7	13	329	69.5	6N,7R

*Normal standard deviations for units having N > 1; original confidence limits from Table 1 for units having N = 1.

**Primed letters indicate fields having low inclinations.

***Age estimate based on K-Ar age of Elkhorn Mountains Volcanics (78.0±1.7 m.y.), which the diorite intrudes, and K-Ar age of Ringing Rocks pluton mafic rocks (78.2±3.1 m.y.), which intrude the diorite.

ment occurred between 68.5 and 78.0 m.y. ago, or during a 10-m.y. span. Without these restrictions based on magnetization data, a time span of 5 to 10 m.y. was inferred from the K-Ar data (Tilling, Klepper, and Obradovich, 1968), depending upon how the rocks were grouped. We conclude that the magnetization data favor a 10-m.y. emplacement span rather than one of 5 m.y. duration.

Field polarity sequence for interval 68 to 78 m.y.—Using the summary of table 3, a field polarity sequence with tentative time boundaries has been established (fig. 5). Polarity boundaries are marked, for simplicity, halfway between successive data points corresponding to opposite polarities. The sequence shows, in order of decreasing age, multiple reversals associated with the Elkhorn Mountains Volcanics between 77 and

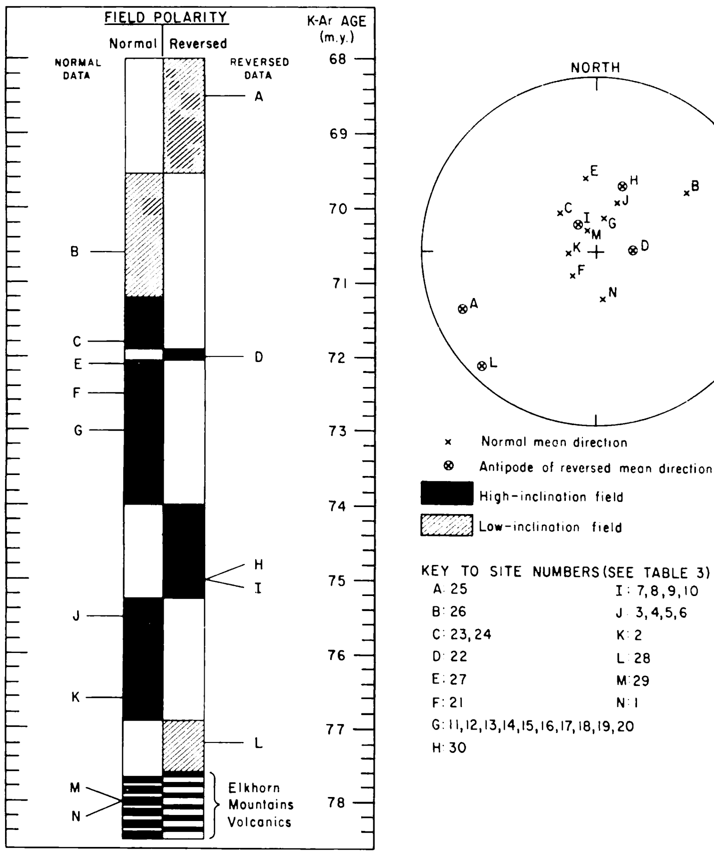

Fig. 5. Inferred field-polarity sequence for the interval 68 to 78 m.y., based on data from the Boulder batholith region, and Lambert lower hemisphere projections of mean magnetization directions used to determine the sequence (see table 3). Polarity boundaries are placed halfway between successive data points of opposite polarity. Placement of Elkhorn Mountains Volcanics reversed periods is arbitrary. Sites 31 and 32 are excluded from analysis because of age uncertainties.

79 m.y. ago and four periods of reversal during emplacement of the batholith. Other reversals that may have occurred during this interval have not been detected because the sampling sites represent a discontinuous time spectrum and K-Ar data are too imprecise to resolve short-term polarity events.

Two reversed periods, at about 68.5 and 77 m.y., have anomalously low field inclinations, as does one normal period at about 70.5 m.y. The duration of these low-inclination field intervals are unknown, but data previously discussed suggest that they are not extremely short-lived. The limited data suggest that reversed periods at about 68.5 and 75 m.y. had 1-m.y. durations, and that those at 72 and 77 m.y. had durations of only a small fraction of a million years.

Age uncertainties in the sequence are to be expected because of the limited precision of K-Ar dating on rocks having so great an age and because of the relatively short time span of emplacement of the individual dated plutons. The amounts of the age uncertainties may be estimated using appropriate statistical parameters, such as "critical values" (Dalrymple and Lamphere, 1969, p. 120), for comparing arithmetic means. In the present context, tests concerning differences between mean ages of the four reversed periods are of most interest because the polarity sequence is founded on the basis of these reversals.

Two tests concerning differences of the means have been applied on the assumptions that the populations of K-Ar dates have normal (Gaussian) frequency distribution and that there is independence within and between samples of dated rocks. The first test further assumed knowledge of population variance, which in the present study was expressed by standard deviations of the ages, ranging from 3.0 to 4.5 percent of the total ages. Alternatively, the second test made no such assumption about population variance values but simply assumed them to be equal and instead made use of the measured sample variances (Student's "t" statistical approach). Comparison of successive mean ages for reversed periods using the first test indicates that mean ages for reversals A and D (fig. 5) are significantly different at a level of confidence between 73 and 90 percent, whereas the second test indicates a significant difference at the 65 percent level. Mean ages for reversals D and HI (fig. 5) are significantly different at a level of confidence between 63 and 83 percent by the first test and at a level of 62 percent of the second test. Means for reversals HI and L (fig. 5) are significantly different at a level between 63 and 82 percent by the first test and at a level of 86 percent by the second test. The main conclusion of these various tests is that the four reversed periods are not all significantly different at the 95 percent level, and that, therefore, the polarity sequence must be considered a tentative construct. It should be emphasized that mean ages of alternate reversed periods (as opposed to succeeding ones) are significantly different at the 95 percent level, lending assurance that a minimum of two reversed periods is represented.

Onset of reversals as a Late Cretaceous time marker.—Paleomagnetic data indicating long periods of normal polarity during the Cretaceous Period, compiled by Helsley and Steiner (1969), suggest that a normal-polarity period of about 30 m.y. preceded the reversed periods inferred from the Elkhorn Mountains Volcanics and Boulder batholith data. Although the presence of reversals within the interval 68 to 78 was predicted from extrapolation of marine magnetic data (Heirtzler and others, 1968), the Boulder batholith data indicate not only the presence of reversals but also the occurrence of anomalous low-inclination directions, which are not easily decipherable from marine magnetic data. In basic agreement with, but in slight contrast to, the suggestion of Sasajima and Shimada (1966) and Sadao Sasajima (written commun., 1968) that a single reversed-polarity interval be used as a worldwide time marker within the Cretaceous Period, the Montana data indicate that the initial time of onset of numerous alternating reversed and normal periods, about 78 m.y. ago, may be useful as a Late Cretaceous time marker. The beginning of Late Cretaceous polarity reversal is not yet precisely fixed, but it is probably within the range of 78 to 80 m.y.

ACKNOWLEDGMENTS

My interest in the Boulder batholith area was inspired by a field trip led by Adolph and Eleanora Knopf in 1961 as part of a National Science Foundation Summer Institute Program coordinated by the Indiana University Geologic Field Station, Cardwell, Montana. This interest grew during subsequent field trips and discussions with R. I. Tilling, H. W. Smedes, M. R. Klepper, and G. D. Robinson of the U.S. Geological Survey, to whom I am also grateful for providing specific information on sampling sites.

Assistance in the Collection and preparation of samples by A. Conradi and measurement of remanent magnetizations by W. E. Huff is acknowledged. E. A. Mankinen provided data on Curie temperature determinations.

APPENDIX A

Detailed sampling site locations

Site 1: lat 46°31.68′N., long. 111°51.26′W. [N½NE¼ sec. 21, T.9 N., R.2 W., East Helena 15′ quadrangle map, scale 1:62,500, 1950].

Site 2: lat 45°56.56′N., long 112°14.30′W. [near center of NW¼ sec. 9, T.2 N., R.5 W., Dry Mountain 7½′ quadrangle map, scale 1:24,000, 1963].

Site 3: lat 46°30.38′N., long. 112°12.46′W. [near northwest corner of SW¼ sec. 26, T.9 N., R.5 W., Helena 15′ quadrangle map, scale 1:62,500, 1950].

Site 4: lat 46°32.04′N., long. 112°00.06′W. [NE¼SE¼ sec. 17, T.9 N., R.3 W., Helena 15′ quadrangle map, scale 1:62,500, 1950].

Site 5: lat 46°31.86′N., long. 111°53.90′W. [S½SE¼ sec. 18, T.9 N., R.2 W., East Helena 15′ quadrangle map, scale 1:62,500, 1950].

Site 6: lat 46°32.58′N., long. 112°05.50′W. [near northwest corner of NE¼ sec. 15, T.9 N., R.4 W., Helena 15′ quadrangle map, scale 1:62,500, 1950].

Site 7: lat 45°50.05′N., long. 112°20.02′W. [NW¼SE¼ sec. 15, T.1 N., R.6 W., Grace 7½′ quadrangle map, scale 1:24,000, 1963].

Site 8: lat 45°49.89′N., long. 112°20.10′W. [near west edge of SW¼SE¼ sec. 15, T.1 N., R.6 W., Grace 7½′ quadrangle map, scale 1:24,000, 1963].

Site 9: lat 45°50.17′N., long. 112°18.90′W. [near center of sec. 14, T.1 N., R.6 W., Grace 7½′ quadrangle map, scale 1:24,000, 1963].

Site 10: lat 45°49.88′N., long. 112°15.72′W. [SW¼SW¼ sec. 17, T.1 N., R.5 W., Grace 7½′ quadrangle map, scale 1:24,000, 1963].
Site 11: lat 46°27.84′N., long. 112°00.12′W. [center of NE¼ sec. 8, T.8 N., R.3 W., Jefferson City 15′ quadrangle map, scale 1:62,500, 1950].
Site 12: lat 46°10.04′N., long. 112°21.80′W. [near center of SW¼ sec. 21, T.5 N., R.6 W., Elk Park 15′ quadrangle map, scale 1:62,500, 1954].
Site 13: lat 46°02.19′N., long. 112°27.54′W. [near center of SW¼ sec. 3, T.3 N., R.7 W., Elk Park 15′ quadrangle map, scale 1:62,500, 1954].
Site 14: lat 45°55.35′N., long. 112°24.90′W. [just south of center of sec. 13, T.2 N., R.7 W., Homestake 7½′ quadrangle map, scale 1:24,000, 1963].
Site 15: lat 45°54.38′N., long 112°27.87′W. [near west edge of SW¼ sec. 22, T.2 N., R.7 W., Homestake 7½′ quadrangle map, scale 1:24,000, 1963].
Site 16: lat 45°54.68±.05′N., long 112°19.80±.05′W. [near center of E½ sec. 22, T.2 N., R.6 W., Delmoe Lake 7½′ quadrangle map, scale 1:24,000, 1963].
Site 17: lat 45°56.04′N., long. 112°14.39′W. [SW¼SW¼ sec. 9, T.2 N., R.5 W., Dry Mountain 7½′ quadrangle map, scale 1:24,000, 1963].
Site 18: lat 46°14.14′N., long. 112°08.62′W. [NE¼NE¼ sec. 31, T.6 N., R.4 W., Boulder 15′ quadrangle map, scale 1:62,500, 1954].
Site 19: lat 46°07.60′N., long. 112°28.00′W. [near northeast corner of SE¼ sec. 4, T.4 N., R.7 W., Elk Park 15′ quadrangle map, scale 1:62,500, 1954].
Site 20: lat 45°55.21′N., long. 112°24.50′W. [near center of SE¼ sec. 13, T.2 N., R.7 W., Homestake 7½′ quadrangle map, scale 1:24,000, 1963].
Site 21: lat 45°50.09′N., long 112°24.43′W. [NE¼SE¼ sec. 13, T.1 N., R.7 W., Pipestone Pass 7½′ quadrangle map, scale 1:24,000, 1963].
Site 22: lat 45°40.74′N., long. 112°22.65′W. [SW¼NW¼ sec. 8, T.2 S., R.6 W., Twin Bridges 15′ quadrangle map, scale 1:62,500, 1960].
Site 23: lat 46°31.19′N., long. 111°56.82′W. [NE¼SW¼ sec. 23, T.9 N., R.3 W., East Helena 15′ quadrangle map, scale 1:62,500, 1950].
Site 24: lat 46°30.25′N., long. 112°03.20′W. [NE¼SW¼ sec. 25, T.9 N., R.4 W., Helena 15′ quadrangle map, scale 1:62,500, 1950].
Site 25: lat 45°49.90′N., long. 112°38.40′W. [SW¼SE¼ sec. 18, T.1 N., R.8 W., Butte South 15′ quadrangle map, scale 1:62,500, 1961].
Site 26: lat 45°51.32′N., long. 112°32.70′W. [near center of NW¼ sec. 12, T.1 N., R.8 W., Butte South 15′ quadrangle map, scale 1:62,500, 1961].
Site 27: lat 46°34.94′N., long. 112°16.23′W. [NW¼NW¼ sec. 32, T. 10 N., R.5 W., Elliston 15′ quadrangle map, scale 1:62,500, 1959].
Site 28: lat 45°46.01′N., long. 112°48.85′W. [SE¼NE¼ sec. 10, T.1 S., R.10 W., Dewey 7½′ quadrangle map, scale 1:24,000, 1961].
Site 29: lat 46°44.92′N., long. 112°17.73′W. [near center of sec. 36, T.12 N., R.6 W., Elliston 15′ quadrangle map, scale 1:62,500, 1959].
Site 30: lat 45°30.83′N., long. 111°59.53′W. [NE¼SE¼ sec. 5, T.4 S., R.3 W., Harrison 15′ quadrangle map, scale 1:62,500, 1950].
Site 31: lat 45°30.16′N., long. 111°41.57′W. [N½SW¼ sec. 11, T.4 S., R.1 W., Norris 15′ quadrangle map, scale 1:62,500, 1949].
Site 32: lat 46°07.80′N., long. 111°38.93′W. [near center of sec. 6, T.4 N., R.1 E., Radersburg 15′ quadrangle map, scale 1:62,500, 1949].

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