Deformation and age of the Red Mountain intrusive system (Urad-Henderson molybdenum deposits), Colorado: Evidence from paleomagnetic and ⁴⁰Ar/³⁹Ar data

JOHN W. GEISSMAN  Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131-1116
LAWRENCE W. SNEE  U.S. Geological Survey, MS 963, Box 25046, Denver Federal Center, Denver, Colorado 80225
GARRETT W. GRAASKAMP  Dunn Geoscience Corp., 5 Northway Lane, North, Latham, New York 12110
ENNIS P. GERAGHTY  Stillwater Mining Company, Box 365, Nye, Montana 59061


ABSTRACT

Paleomagnetic and ⁴⁰Ar/³⁹Ar age-spectra data from most stocks of the Red Mountain intrusive system, in the northwest Colorado mineral belt, provide an improved understanding of the structural and cooling history of the suite of intrusions hosted to a world-class molybdenum deposit. Paleomagnetic data from five stocks at the surface and eight younger stocks exposed in the subsurface Henderson Mine support field observations (for example, dike and vein orientations, stock geometries, and distributions of zones of mineralization) that imply moderate tilting (15°–25° down to the east-southeast) since latest Oligocene time after cooling and mineralization. Surface stocks contain magnetizations carried by both magnetite and hematite. The Red Mountain stock is the youngest surface intrusion and contains mostly normal polarity magnetizations (for example, D = 321°, I = 59°, α₉⁵ = 19°, k = 9, N = 6 samples, site RM9), whereas older East Knob and Rubble Rock breccia intrusions contain a nearly antipodal, well-characterized magnetization (East Knob stock: declination = 161°, inclination = −47°, α₉⁵ = 13°, k = 23, average of five site means). Polarity changed from reverse to normal during emplacement and cooling of the Red Mountain intrusions exposed at the surface. ⁴⁰Ar/³⁹Ar age-spectrum data on biotite and orthoclase from the Red Mountain stock and stocks of the Henderson Mine indicate the reversal to be older than 30 Ma. All Henderson Mine stocks have normal polarity magnetizations (Primos stock: D = 333°, I = 51°, α₉⁵ = 5°, k = 44, average of six site means) which, on the basis of ⁴⁰Ar/³⁹Ar age spectra from orthoclase and biotite, were blocked between 28.7 and 27.6 Ma. Magnetite and maghemite are the major carriers of magnetization in these rocks.

On the basis of an ⁴⁰Ar/³⁹Ar thermochronologic study of the Red Mountain intrusive system, thermal activity started at or just before 29.9 ± 0.3 Ma and ended at 26.95 ± 0.08 Ma. The age-spectrum data are interpreted to indicate that the porphyry of Red Mountain, one of the oldest stocks, was emplaced before 29.9 ± 0.3 Ma (possibly before 30.38 ± 0.09 Ma). Nearby lamprophyre dikes were emplaced at 29.8 ± 0.1 Ma; rhyolite dikes intruded at 29.4 ± 0.2 Ma. The Urad and Seriate stocks intruded after 29.8 Ma but before emplacement of the Vasquez stock at 28.71 ± 0.08 Ma. The system core cooled below 280 ± 40 °C (the argon closure temperature of biotite) at 27.59 ± 0.03 Ma. The last period of thermal activity involved pulses of magnetite-sericite alteration around the Seriate stock between 27.51 ± 0.03 and 26.95 ± 0.08 Ma; this activity did not thermally overprint unaltered parts of the intrusive system.

Tilting of the Red Mountain area is implied by a comparison between a grand mean (on the basis of 10 stock means, D = 333°, I = 49°, α₉⁵ = 5°, k = 78) and a mid-Tertiary reference field. The Red Mountain intrusive system and host Precambrian rocks probably were deformed along a nearly north-south horizontal axis in response to northwest-side down, strike-slip faulting with displacement largely along the Woods Creek fault zone. Late Tertiary deformation of Precambrian-cored parts of the Front Range, host to numerous mineral deposits, was more complicated than simple, near-vertical uplift of the crust.

INTRODUCTION

Paleomagnetic methods are useful for quantifying crustal deformation within regions of greatly varied scale. For batholiths and stocks, paleomagnetic analysis is one of the few methods by which total deformation may be inferred (Beck, 1980; Geissman and others, 1980; Geissman and others, 1982; Shaver and Williams, 1987; Faulds and others, 1992). The lack of conventional reference to the paleohorizontal datum, however, at the time during which magnetization was acquired has occasionally led to controversy over the interpretation of paleomagnetic data from large, batholithic terranes (Beck, 1980; Butler and others, 1991; Marquis and Irving, 1990; Irving and Thorkelson, 1990). Other methods may allow estimation of the paleohorizontal datum. Whole-rock and mineral chemistry, isotope data, and field studies allowed Barnes and others (1986a) and Barnes and others (1986b) to infer postcrystallization tilting of Mesozoic plutons in the Klamath Mountains. Petrologic studies of the Jurassic Yerington batholith, west-central Nevada, led Dilles (1987) to corroborate structural (Proffett, 1977) and paleomagnetic (Geissman and others, 1982) investigations that indicated about 70°–90° tilting of the intrusions and wall rocks.

Structural setting is important in the exploration for and resource evaluation of mineral deposits in intrusive rocks. Nonetheless, because of complications resulting from complete or partial thermal and/or chemical remagnetization, few paleomagnetic studies have focused on complex, multiple-intrusion and hydrothermally mineralized systems. Particular concerns are the time at which magnetization was acquired relative to the time of system intrusion and tempora-
ture changes during intrusion and alteration. These may be answered by \( ^{40}\text{Ar}/^{39}\text{Ar} \) age-spectrum data on different mineral phases with different argon closure temperatures.

At the Red Mountain intrusive system, in the Front Range in Colorado (Fig. 1), late Oligocene stocks host the Urad (surface) and Henderson (underground) porphyry molybdenum deposits (Wallace and others, 1978; Garten and others, 1988). Several field relationships imply that after mineralization the Red Mountain system may have been tilted in latest Oligocene and younger time. These include the asymmetrical orientation of intrusive contacts, radial dikes, and veins as well as the asymmetrical distribution of intrusive textures, alteration facies and ore zones (Wallace and others, 1978; Carten and others, 1988; Geraghty and others, 1988).

The system intrudes Middle Proterozoic Silver Plume Granite and, therefore, the paleohorizontal plane at the time of intrusion cannot be referenced. The nearest outcrops of Phanerozoic strata are 18 km to the northwest in the Fraser Basin south of Granby (Fig. 1). Differentiating asymmetries caused by deformation from those related to intrusion bears on continued exploration and development of the deeper levels of the Henderson deposit as well as the Neogene structural setting of the Front Range.

Paleomagnetic and \( ^{40}\text{Ar}/^{39}\text{Ar} \) age-spectrum data obtained from most surface and subsurface intrusions provide an improved understanding of the structural and cooling history of the intrusive system; many of our observations may be applicable to other porphyry systems. The paleomagnetic data support geologic evidence for 15°-25° of down to the east-southeast tilting of the system in latest Oligocene time. Both field structural and paleomagnetic data have simultaneously documented a paleomagnetically measurable amount of local tilting of a series of shallow stocks. The presence of dual polarity magnetizations indicates that stocks cooled during at least one geomagnetic field polarity reversal (from reverse to normal polarity) before about 30 Ma and that later thermochemical activity during one or more normal polarity chrons did not unblock the reverse polarity magnetization. \( ^{40}\text{Ar}/^{39}\text{Ar} \) age-spectrum data identify the episodic nature of intrusion and alteration; they are interpreted to indicate that cooling below biotite argon-closure temperature of the entire intrusive system after emplacement of the underground stocks occurred in about \( 2 \times 10^6 \) years. Paleomagnetic and \( ^{40}\text{Ar}/^{39}\text{Ar} \) age-spectrum methods used in this study are summarized in the Appendix.

The \( ^{40}\text{Ar}/^{39}\text{Ar} \) age-spectrum data presented below are summarized from an ongoing study (L. W. Snee and R. B. Carten, 1990, U.S. Geological Survey, unpub. data) on the Red Mountain intrusive system and related Urad-Henderson mineral deposit. All argon data and their interpretation are included in a forthcoming paper to focus on the age and thermal history of plutons and alteration within the intrusive system as well as the origin of the Urad-Henderson deposit. Because of the importance of high-resolution cooling ages for interpretation of the paleomagnetic results presented here, however, we include interpreted cooling ages, composite age-spectrum diagrams, and an interpreted thermal history derived from these unpublished argon data. We summarize all existing geochronologic data from previous published and unpublished studies for completeness. The \( ^{40}\text{Ar}/^{39}\text{Ar} \) data are favored in the interpretations presented below because of higher precision, in some cases as good as 0.1% or 30,000 years.

**GENERAL GEOLOGY**

The Red Mountain intrusive system lies within the 1.4-Ga Silver Plume Granite batholith (Fig. 2). The northeast-striking Berthoud Pass and north-striking Vasquez Pass faults are...
The Red Mountain intrusive system is made up of 15 major stocks and 4 igneous breccia zones. Of these 19 stocks and breccia zones, 13 were sampled for paleomagnetic study; from oldest to youngest they are as follows: breccia of East Knob, breccia of Rubble Rock, Red Mountain intrusive system, Colorado. 1033

Figure 2. Generalized surface geology of Red Mountain; modified from Wallace and others (1978) and Geraghty and others (1988). Solid circles are numbered paleomagnetic sampling sites. Medium heavy lines are dikes and small intrusive bodies. D, U = down, up.

Continuous for several tens of kilometers in the Front Range in Colorado and pass within 2 km of the system (Figs. 1 and 2). The intrusive system is bounded by the Woods Creek fault, a northeast-striking strand of the Berthoud Pass fault, the Vasquez Pass fault, and a suspected east-striking fault in the valley of the West Fork of Clear Creek (Theobald and others, 1983; Figs. 1 and 2). The specific geology of the Urad and Henderson deposits and the Red Mountain area in general has been discussed by Wallace and others (1978), White and others (1981), Carten and others (1988), Lovering and Goddard (1950), Tweto and Sims (1963), and Theobald (1965).

The Red Mountain intrusive system is made up of 15 major stocks and 4 igneous breccia zones. Of these 19 stocks and breccia zones, 13 were sampled for paleomagnetic study; from oldest to youngest they are as follows: breccia of East Knob, breccia of Rubble Rock, Red Mountain intrusive system, Colorado. 1033

Figure 3. Location of numbered subsurface paleomagnetic sampling sites (solid circles) with respect to stocks in the Henderson Mine, projected to the 7,500-ft (2,330-m) level. Geology modified from Wallace and others (1978). Lettered stocks are as follows: H, Henderson; P, Primos; S, Seriate; B, Berthoud; A, Arapaho; R, Ruby; N, Nystrom. Dashed lines refer to fact that the Arapaho and Berthoud stocks are not exposed at the 7,500-ft level. East/north coordinates are specific to the Henderson Mine.
tain border, porphyry of Red Mountain, igneous-fragmental breccia (all exposed at the surface), Urad, Berthoud, Henderson, Primes, Arapaho, Seriate, Ruby, and Nystrom (Fig. 3). All stocks and fragments in intrusion breccia are similar in chemistry and mineralogy and consist of quartz, alkali feldspar, albitic plagioclase, and minor biotite. The surface rocks are generally porphyritic and locally exhibit elastic and/or fragmental textures consistent with subvolcanic emplacement. Sample sites on the surface of Red Mountain lie within a general zone of phyllitic quartz-sericite-pyrite alteration and a more distant outer zone of argillic alteration (MacKenzie, 1970). These rocks contain abundant hematite, presumably formed during alteration of pyrite, biotite, and/or magnetite. The paleomagnetic data discussed below suggest, but do not conclusively prove, that oxidation occurred during hydrothermal activity, not during recent, near-surface weathering. At most subsurface sites (Henderson Mine, ~1.3 km below the surface of Red Mountain), intrusions are porphyritic-aplitic to equigranular in texture. With respect to our collection for paleomagnetic investigation, the type and intensity of hydrothermal alteration and degree of molybdenum mineralization vary among individual samples from a site and among specimens from a given sample. Typically, secondary sericite and kaolinite (Walker, 1984) partially replace feldspar at many sites.

Field relations suggest that the intrusive system was not emplaced in its present, off-vertical orientation. First, mineralized rocks and high-silica alteration halos delineated underground are best developed southeast of the apical parts of mineralizing stocks (Garten and others, 1988). Second, primary igneous textures within individual stocks (Shannon and others, 1982) and geometries of stock contacts imply that structurally higher levels of stocks presently are at lower elevations on their southeast sides than on their northwest sides. Third, radial dikes exposed on the surface and radial vein sets exposed underground in the Henderson Mine are markedly asymmetric in orientation. The dike and vein orientations imply either a nonvertical principal stress direction during dike emplacement or tilting (rotation about a near-horizontal axis) of the system after intrusion, hydrothermal alteration, and mineralization (Geraghty and others, 1988).

### PALEOMAGNETIC RESULTS

#### Red Mountain Surface Stocks

Magnetizations from samples of the five intrusions (nine sites) on Red Mountain are reasonably well defined and suggest acquisition over a time period of reverse and then normal polarity. Median destructive inductions (MDI) in alternating field (AF) demagnetization (the peak induction required to reduce the natural remanent magnetization [NRM] intensity to half the original value) commonly exceed 15 millitesla (mT). For MDI's exceeding 15 mT, the NRM is carried predominantly by fine (pseudo-single- or single-domain) magnetite, maghemite, and (or) hematite. Magnetizations carried by hematite (with unblocking temperatures greater than ~580 °C and MDI's >100 mT) are usually similar in direction to those residing in magnetite, unblocked at lower temperatures.

The two oldest intrusions are breccias (East Knob and Rubble Rock); they contain magnetizations of southeast declination and moderate upward (negative) inclination (Figs. 4 and 5A). We interpret this magnetization as a reverse-polarity-thermoremanent magnetization (TRM) characteristic of the rocks. In single-component magnetizations, the reverse-polarity characteris-

![Figure 4](image-url)
tic magnetization usually resides in magnetite (see, Figs. 4A and 4B), but commonly much of the NRM is carried in hematite, as revealed in thermal demagnetization. Although short (~10,000 yr) reversed-polarity subchrons occurred during the Brunhes normal polarity chron (ca. 730 Ka to present) (Champion and others, 1987), magnetizations of reverse polarity carried by hematite were probably not acquired during recent weathering. The relationship is more complicated where behavior is multicomponent, such as site 3 in porphyry at East Knob. The reverse-polarity remanence in site 3 samples is carried by both hematite (see Fig. 4D) and magnetite (see Fig. 4C). When magnetite carries the reverse-polarity magnetization, higher unblocking temperature magnetizations residing in hematite are of positive inclination yet are dispersed in declination.

The border and porphyry phases of the Red Mountain stock and the igne-fragmental breccia cut the East Knob and Rubble Rock breccia stocks. These younger intrusions contain magnetizations of mixed polarity, but the magnetizations are predominantly of northwest declination and moderate positive inclination (normal polarity). The remanence is carried by magnetite and hematite. Using the paleomagnetic data summarized in Table 1, we infer that intrusion of stocks exposed on Red Mountain spanned at least one field reversal.

Magnetizations carried by hematite in the Red Mountain intrusions may have been acquired over a prolonged period of oxidation that spanned several polarity chrons. In some rocks, more than 80% of the NRM is carried by hematite. Because the directions of magnetizations carried by hematite generally parallel those residing in magnetite, we suggest that the magnetizations in hematite record an ambient field; the magnetizations could have been acquired during the same polarity chron as when a TRM was blocked in magnetite. We assume that the use of magnetizations residing in hematite, as well as those in magnetite, is reasonable for structural interpretations.

Henderson Mine Stocks

All eight intrusions (30 sites) sampled in the Henderson Mine are characterized by a normal polarity magnetization, in contrast to the surface stocks which are principally of reverse polarity (Table 2 and Table 3). The magnetization isolated in all intrusions has north-northwest declination and moderate positive inclination (Fig. 6), although the amount of within-site dispersion varies considerably (Fig. 5B). Probable contributors to the within-site dispersion of directions are discussed below. In specimens with multicomponent magnetizations, the first-removed component usually has a more northward declination and steeper positive inclination (such as specimen HEN1981a, Fig. 6E). In total, NRM directions are somewhat dispersed, but a well-defined, reverse polarity secondary magnetization was not defined for any site or individual intrusion. Unlike the surface rocks, magnetite and possibly maghemite are the only magnetization carriers, because the intensity of magnetizations remaining above ~580 °C never exceeded a few percent of the original NRM intensity. MDI's for most rocks containing magnetite as the principal magnetic phase are <15 mT, sug-

<table>
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<th>Site</th>
<th>Mean decl.</th>
<th>Mean incl.</th>
<th>MDI</th>
<th>n/</th>
<th>n/</th>
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<td>5</td>
<td>20/20/8</td>
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<td>14/14/8</td>
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*All sites are shown in Figure 2.
† Semi-angle of the cone of 95% confidence around the calculated mean direction.
‡ Best estimate of the precision of the distribution of the n magnetization vectors (Fisher, 1953).
§ MDI of specimen.
gesting that multidomain grains carry much of the NRM.

MAGNETIC MINERALOGY AND ROCK MAGNETISM

The history of the Red Mountain intrusive system includes a complex series of igneous as well as hydrothermal mineralization and alteration events (White and others, 1981; Carter and others, 1988). Observations on the magnetic phases that carry geologically important magnetizations may limit the age of magnetization acquisition relative to subsolidus cooling, alteration, and later uplift and local deformation.

Red Mountain Surface Stocks

Sample response to progressive demagnetization, rock magnetic tests, and petrographic examination all indicate that the principal magnetic phases in the surface intrusions are magnetite, hematite, and goethite (Fig. 7). Textural relations suggest that hematite and goethite have replaced pyrite and magnetite. Pyrite precipitated during hydrothermal mineralization and alteration; magnetite is of magmatic origin. Intensities of the NRM for the Red Mountain surface intrusions are low; mean values for each intrusion range from 140 to 2 milliampere-meter (mA/m). Such low NRM intensities attest to a very low concentration of magnetic phases, especially of magnetite.

Isothermal remnant magnetization (IRM) acquisition curves usually increase gradually in magnetization to as much as 1.2 T, but never reach saturation. The lack of abrupt increase in IRM in inductions less than 0.3 T implies that high coercivity phases predominate in the surface intrusions. Where enough magnetite could be separated from these surface rocks, poorly defined saturation magnetization versus temperature curves indicate Curie temperatures between 550 and 585 °C, indicative of low-Ti magnetite as the saturated phase.

The magnetic properties of samples from individual stocks, as well as from individual sites, are varied which leads to some between-site variations in dispersion of magnetization data. As mentioned above, demagnetization results from site RMT3 (Fig. 8) in the East Knob stock exemplify such variations. In thermal demagnetization, specimens from samples G and I exhibit magnetization unblocking temperatures below 550 °C; those of specimens from samples D and F are above 650 °C. In AF demagnetization, behavior of duplicate specimens indicated dominance by magnetite (samples G and I) and hematite (samples D and F).

Henderson Mine Stocks

Magnetization carriers in the Henderson Mine stocks are magnetite and probably maghemite. IRM acquisition curves show nearly complete saturation by about 0.3 T which indicates dominance by moderate- to low-coercivity cubic phases. Hematite was not an equilibrium mineral phase during molybdenite mineralization (Drabek, 1982; Carter and others, 1988), and subsequent oxidation of magnetite and pyrite to hematite has been fairly minor in the underground stocks. NRM intensities for the underground rocks are also low; mean values for each intrusion range from 3.5 to 40 mA/m. Again, such low NRM intensities imply only small amounts of cubic magnetic phases. If fine (magnetically single domain) grains carry the magnetization, then a TMR of 5 mA/m could reside in grains whose volume fraction is less than $2.6 \times 10^{-5}$ (Sugita, 1979).

Magnetite grains are predominantly inclu-
Figure 6. Orthogonal progressive demagnetization diagrams (Zijderveld, 1967) of representative response by Henderson Mine rocks. The endpoint of the magnetization vector is simultaneously projected onto two orthogonal planes (horizontal: E-W/N-S plane, solid symbols; vertical, E-W or N-S/U-D plane, open symbols). Peak demagnetizing inductions (in mT) or temperatures (°C) are given adjacent to data points on the vertical projections. Data are plotted in geographic coordinates. Specimen identifier is given before a brief description of the rock. Magnetizations isolated in progressive demagnetization and determined using principal component analysis are as follows: (A) 334°/50°, MAD = 7.7°, 42-mT origin. (B) A comparison of response to thermal and AF demagnetization; thermal: 344°/57°, MAD = 2.3°, 300–500 °C, AF; high median destructive inductions of samples from this site preclude isolation of a well-defined component of magnetization. (C) 330°/38°, MAD = 3.5°, 25–100 mT. (D) 338°/42°, MAD = 15.9°, 18–95 mT. (E) 330°/58°, MAD = 1.8°, 8–50 mT.
Figure 7. Reflected light photomicrographs of Fe-Ti oxide parageneses in Henderson Mine subsurface stocks. The scale bar in each photomicrograph is 10 microns. (A) Magnetite (mt) surrounded by sphene (s), HEN13C; (B) subangular magnetite grains, HEN13C; (C) subangular magnetite (mt) and pyrite (py) in potassium feldspar, HEN25D; (D) magnetite (mt) rimmed by hematite (hm), HEN23A; (E) magnetite formed along cleavage planes in biotite host, HEN23A.

Figure 8. Normalized intensity ($J/J_0$) decay curves for eight specimens from samples of porphyry from Red Mountain, site RMT3. Open squares indicate results of AF demagnetization, open circles for thermal treatment. Capital letters refer to discrete samples from site RMT3.
Ozdemir and Banerjee, 1984). Keefer and Shive (1980) reported inversion temperatures of 500 °C for pure maghemite and 360 °C for maghemite of oxidation parameter z = 0.5. Ozdemir and Banerjee (1984) found synthetic, single-domain maghemite to remain stable below ~510 °C and probably to higher temperatures. The discrepancy between experimental and observed inversion temperatures may lie in the fact that Ozdemir and Banerjee (1984) heated samples at a rate of 10–20 °C/min. In thermal demagnetization, samples are heated at a fixed temperature for at least 30 min. To account for the observed high MDI's in maghemite, the magnetization must be contained largely in grains less than a few microns in diameter (Danks, 1979). Coarse, multidomain magnetite is present in small quantities at these sites.

The low unblocking-temperature magnetization could not reside in high-Ti titanomaghemite grains for which Curie temperatures are <400 °C, because all magnetite in the Henderson system contains <1.0 wt% TiO₂ (Seedorf, 1987). If samples are heated as Curie and laboratory unblocking temperatures are measured, then saturation magnetization and NRM intensity do not increase. Single-domain, low-Ti magnetite grains near the superparamagnetic threshold have low unblocking temperatures (Dunlop, 1973), but Curie temperatures >600 °C would not be expected. Lastly, fine-grained pyrrhotite is also not likely to carry the low unblocking temperature magnetization. This phase is spatially restricted within the Henderson system, and these regions were not sampled in the present investigation.

We conclude that low-Ti maghemite carries the low unblocking temperature and high-MDI magnetization in some of the Henderson stocks, and that the maghemite formed during low-temperature oxidation of fine magnetite at temperatures <400 °C during alteration and thermal decay of the hydrothermal system. The presence of maghemite, although pervasive on a site level, is not specifically related to an individual pluton. Rather, it appears related to the intensity of quartz-sericite-pyrite alteration.

Is the maghemite-dominated magnetization in these rocks an accurate recorder of the field at the time of acquisition? Experiments producing fine-grained, low-Ti maghemite from single-domain magnetite particles (Johnson and Merrill, 1974; Heider and Dunlop, 1987) have shown that the initial remanence carried by magnetite is preserved in single-phase oxidation to a cation-deficient spinel, regardless of the direction of the field during oxidation. If realistic for natural conditions, the experimental data imply that an original TRM acquired by magnetite during blocking below 580 °C could still be retained in the most extreme conditions of pervasive maghemitization of Henderson stocks.

**40Ar/39Ar RESULTS**

Fission-track and K/Ar isotopic dates from earlier studies (Table 4; Naeser and others, 1973; Shannon, 1982) poorly define the age of the Red Mountain intrusive system between 23.8 ± 2.3 and 34.4 ± 1.7 Ma. This wide range in dates possibly reflects thermal complexities that resulted from the emplacement of many closely spaced intrusions, the effect of subsequent alteration of dated phases, and subsequent cooling of dated phases through corresponding isotopic closure temperatures. In contrast, the 40Ar/39Ar age-spectrum dates (Table 4; L. W. Snee and R. B. Carten, U.S. Geological Survey, unpub. data) range between 26.95 ± 0.08 and 29.9 ± 0.3 Ma; all 40Ar/39Ar dates are reasonable when compared to geologic relationships. These dates were obtained on biotite, orthoclase, and muscovite; isotopic closure temperatures are about 280 ± 40, 350 ± 50, and 325 ± 25 °C, respectively, assuming moderately high (>25 °C/10^10/2) rates of cooling (Snee, 1982; McDougall and Harrison, 1988; Snee and others, 1988).
In most cases, the age spectra are well defined; in a few (best exhibited in Figs. 11A and 11B), excess argon or argon loss are recorded in initial release of $^{39}\text{Ar}$. On the basis of the $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra (Fig. 11), the emplacement and cooling history of the Red Mountain intrusive system, summarized in Table 5, is as follows:

1. We interpret the age spectrum for orthoclase from the porphyry of Red Mountain (Fig. 11A) as an indication that the intrusion cooled below $\sim 350 \degree C$ (orthoclase closure temperature) following its emplacement before $\sim 29.9 \pm 0.3 \text{ Ma}$ (a "preferred age" based on an average of last 60% of the age spectrum) and possibly before $30.38 \pm 0.09 \text{ Ma}$ (apparent age of the last temperature step). The age spectrum is disturbed and exhibits minor excess argon in the lower temperature steps and evidence for a thermal disturbance at $\sim 26.9 \text{ Ma}$.

2. Lamprophyre dikes were emplaced at $\sim 29.8 \pm 0.1 \text{ Ma}$ and rhyolite dikes were emplaced at about $29.4 \pm 0.2 \text{ Ma}$. These emplacement ages are based on data for biotite from a lamprophyre dike (age spectrum not shown in Fig. 11) and orthoclase from the rhyolite dike (Fig. 11A).

3. The Urad and Seriate stocks were emplaced before $28.71 \pm 0.08 \text{ Ma}$, which is the interpreted age of emplacement of the Vasquez stock. The Ute stock was emplaced between $28.7$ and $28.4 \text{ Ma}$. These interpretations are derived from five orthoclase and one biotite age spectra shown in Figure 11B.

4. The central part, or core, of the intrusive system cooled below $280 \degree C$ at $27.59 \pm 0.03 \text{ Ma}$. Age spectra for six biotites from the Henderson, Ute, Vasquez, and Seriate stocks within the core of the system (Fig. 11C) are statistically indistinguishable in age and represent the time during which the system cooled below the argon closure temperature of biotite ($\sim 280 \pm 40 \degree C$).

5. The magnetite-sericite alteration zone around the Seriate stock formed between $27.51 \pm 0.03$ and $26.95 \pm 0.08 \text{ Ma}$ based on $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for three muscovites (Fig. 11D) crystallized during this event. One of these muscovites is statistically older than the two younger muscovites; this suggests that magnetite-sericite alteration affected different parts of the alteration zone at different times. An altered orthoclase from the Seriate stock has a $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum (Fig. 11) of $27.13 \pm 0.17 \text{ Ma}$ and was probably affected during the magnetite-sericite alteration event. In general, however, the lack of thermal overprint on unaltered parts of the Red Mountain intrusive system indicates that the thermal effect from the magnetite-sericite alteration was limited. The interpreted $^{40}\text{Ar}/^{39}\text{Ar}$ age-spectrum data are consistent with observed cross-cutting relations and define the emplacement, cooling, and alteration history of the system (Fig. 12).

**DISCUSSION**

Overall, paleomagnetic data from stocks of the Red Mountain intrusive system are well grouped on both between-site and between-stock levels. East Knob and Rubble Rock breccia stocks on the surface of Red Mountain contain characteristic magnetizations of reverse polarity. All younger surface stocks contain magnetizations of mixed polarity. Henderson Mine stocks contain only normal polarity magnetizations, but a $95\%$-confidence level (McFadden and Lowes, 1981), to those of reverse polarity. Magnetizations defined in progressive demagnetization do not cluster about present-day or time-averaged Quaternary field directions. We suggest that the paleomagnetic data adequately represent a late Oligocene field
and that the results may be used to assess structural deformation of the intrusive system and host Precambrian rocks. Before discussion of the structural history, we address the dispersion of paleomagnetic data.

Dispersion of Magnetization Data

Potential contributions to within-site dispersion of data from the intrusive system include sampling and data reduction errors; irregular, prolonged thermal histories of parts of stocks; and acquisition of CRM's in hematite and maghemite during alteration of primary magnetic or precipitation of secondary magnetic phases.

For both surface and subsurface sites, within-site dispersion is affected by occasional inaccuracy in sample orientation and/or collection of in-situ material. Red Mountain is rugged, steep, and largely covered with talus. Although we attempted to collect samples broadly over undisturbed outcrops, parts of outcrops may be slumped. In subsurface, the fragmentary rocks and minor, local, magnetic field disturbances, for which we could not fully account, may have increased dispersion. As much as 5° of angular dispersion may be due to errors in sampling. We were not able to apply principal components analysis to results from the entire collection because of an unfortunate accident destroying all records of most demagnetization data after vector subtraction was applied. Where possible, comparison of results of both methods yields vector differences as large as 5°. Differences are not systematic, however, and the contribution to the total dispersion as a result of using the vector subtraction technique is less than this value.

**Figure 11.** Composite $^{40}$Ar/$^{39}$Ar age-spectrum diagram for orthoclase, muscovite, and biotite from the Red Mountain intrusive system. (One sigma analytical errors for data for most statistically significant temperature steps are between 0.06 and 0.10 Ma.) (A) Age-spectrum for orthoclase from porphyry of Red Mountain and potassium feldspar from a rhyolite dike emplaced into Precambrian host rocks. (B) Six (five orthoclase, one biotite) age spectra for minerals from the Urad, Seriate, Henderson, Ute, and Vasquez stocks. (C) Six age spectra for biotites from Henderson, Ute, Vasquez, and Seriate stocks within the central part of the Red Mountain intrusive system. (D) Three age spectra for muscovite from the magnetite-sericite alteration zone around the Seriate stock.

**Figure 12.** Schematic block diagram of the Red Mountain intrusive system showing relative ages of stocks and cooling of emplacement (see Table 5); all ages in millions of years. Dashed lines represent approximate contacts between intrusions. Stippled region represents approximately the part of the system that cooled below $280\,^\circ$C at 27.59 ± 0.03 Ma on the basis of six biotite $^{40}$Ar/$^{39}$Ar dates. Patterned region represents area of magnetite-sericite alteration formed between $27.51 \pm 0.03$ and $26.95 \pm 0.08$ Ma at the end of system cooling.

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**TABLE 5. SUMMARY OF INTERPRETED $^{40}$Ar/$^{39}$Ar THERMOCRONOLOGY, MAGNETIZATION ACQUISITION AND STRUCTURAL EVENTS, RED MOUNTAIN INTRUSIVE SYSTEM**

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>Part of system</th>
<th>Geologic activity (i.e., thermal event)</th>
<th>Effect of event on magnetization</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-26</td>
<td>Entire system</td>
<td>Tiling</td>
<td>ESE-side down</td>
</tr>
<tr>
<td>26.95 ± 0.08 to 27.51 ± 0.03</td>
<td>Seriate stock</td>
<td>Magnetite-sericite alteration</td>
<td></td>
</tr>
<tr>
<td>27.59 ± 0.03</td>
<td>Core of system</td>
<td>Cooled below $280,^\circ$C</td>
<td>Normal polarity of Henderson Mine stocks completely blocked</td>
</tr>
<tr>
<td>&gt;28.4 + 0.3</td>
<td>Ute stock</td>
<td>Emplacement</td>
<td></td>
</tr>
<tr>
<td>&gt;28.71 ± 0.08</td>
<td>Vasquez stock</td>
<td>Emplacement</td>
<td></td>
</tr>
<tr>
<td>&gt;29.51 ± 0.08</td>
<td>Seriate and Henderson stocks</td>
<td>Emplacement</td>
<td></td>
</tr>
<tr>
<td>&gt;29.71 ± 0.08</td>
<td>Urad porphyry</td>
<td>Emplacement</td>
<td></td>
</tr>
<tr>
<td>29.4 and 29.8</td>
<td>Lamprophyres and rhyolite dikes</td>
<td>Emplacement in Silver Plume Granite</td>
<td>Reverse to normal polarity reversal</td>
</tr>
<tr>
<td>&gt;29.83 ± 0.34</td>
<td>Porphyry of Red Mountain and older surface stocks</td>
<td>Emplacement in Silver Plume Granite</td>
<td>Reverse to normal polarity reversal</td>
</tr>
<tr>
<td>possibly 30.28 ± 0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Some dispersion of data from a single site or stock must be attributed to processes affecting volumes as small as individual specimens. Demagnetization of at least six specimens per sample permitted estimation of within-sample dispersion for several randomly chosen samples. As an example, six specimens from sample 8C (site HEN8 in the Seriate stock) give a mean direction with declination of 358° and inclination of +57° ($\alpha_{95} = 12.9^\circ$, $k = 27.8$). Although between-specimen dispersion is usually less than that between samples (within site), implying sample-orientation errors, between-specimen dispersion may be considerable. Magnetizations in the Red Mountain stocks, each with a cross section on the order of 0.04 to 0.09 km$^2$ at the elevation of the Henderson Mine, were acquired over several thousand years, if not considerably longer, during blocking below 580 °C and alteration. For the surface rocks with abundant hematite, at least part of the dispersion may arise from alteration, because Heider and Dunlop (1987) showed that secondary magnetizations acquired during the oxidation of magnetite to hematite may have no record of either a pre-existing magnetization or the ambient field attending alteration.

Within-site dispersion of all Henderson stocks may also reflect past secular variation, and this dispersion may be compared with predicted angular variance values on the basis of models of field variations. Although data from young lava flows compare favorably with model predictions, we are not sure whether data from slowly cooled intrusions can be compared with values provided by such models. For a site latitude of 39.8°, McFadden and Mclnthinny's (1984) paleosecular variation model for Cenozoic virtual geomagnetic pole (VGP) data predicts a VGP angular dispersion of 16.3°. McFadden and others' (1988) model G, on the basis of data from lavas <5 Ma in age, predicts a value of 16.1°. Individual sites and individual stocks of the Red Mountain intrusive system have angular dispersions that usually exceed 15°, suggesting that magnetizations were acquired over extended time periods.

**Deformation of the Red Mountain Intrusive System**

Wallace and others (1978) recognized the asymmetry of the Henderson deposit and suggested that parts of the deposit might have been deformed since stock emplacement and mineralization. Field evidence described by Geraghty and others (1988) suggests that Red Mountain has been tilted in an east-southeast–side-down fashion.

Stocks of the intrusive system give magnetizations of northwest declination and moderate positive inclination (and antipodes); they do not resemble mid-Cenozoic reference directions. The tight grouping of pluton mean directions, which themselves are moderately dispersed, and the presence of dual polarities suggest that the late Oligocene field has been time averaged by the ensemble of all stocks.

Grand mean directions for the intrusive system (Fig. 13) were determined in two ways (Table 3). We first used mean directions from the 10 stocks for which $\alpha_{95}$ values were <15° (Tables 1 and 2). The mean directions from the remaining three stocks are statistically identical to the overall mean for the complex at a 95%-confidence level (McFadden and Lowes, 1981), yet they are determined at a poor level of precision. Alternatively, we assumed that each site, rather than each stock, provided an independent record of an ambient field, resulting from a complicated cooling and alteration history. All site means that had $\alpha_{95}$ values of <20° (34 of 39 sites) were included. The mean determined by this method is statistically indistinguishable, at a 99%-probability level (McFadden and Lowes, 1981), from that determined using stock means. The pluton means yield a VGP angular variance of 1.7°, whereas the site means yield a VGP angular variance of 12.5°, values less than those for individual samples, sites, and stocks. The 12.5° variance is closer to that expected for a small number of independent field observations. We interpret the small angular-dispersion value derived from stock means to imply an averaging of the late Oligocene field by each stock.

Expected time-averaged geomagnetic field directions for central Colorado (Fig. 13) have been calculated from paleomagnetic poles compiled by Irving and Irving (1982) (30 Ma mean) and Diehl and others (1983, 1988) (38–22 Ma results). In-situ magnetizations from the intrusive system are discordant in both declination (westward) and inclination (shallow) from either of the above reference directions. The discrepancy between observed and expected directions may be explained by rotation about one structural axis or a combination of several axes of differing orientations. Given the absence of late Oligocene and younger strata near Red Mountain, we evaluate the discrepancy in terms of a single event that uniformly deformed the entire Red Mountain area. This approach may reveal that a particular bounding fault or set of faults controlled structural adjustment. Deformation in all likelihood consisted of a more complicated sequence of movements involving differential adjustments on several bounding faults.

Because the discrepancy in paleomagnetic inclination is less than that in declination, single-step deformations are of two types. The first is true counterclockwise rotation about near-vertical axes in response to shear along a single fault or sets of faults bounding Red Mountain. This mechanism is unlikely given the required amount of rotation for all orientations of rotational axes that could be related to known structures. On both local and regional scales, there is no evidence to suggest an amount of strike-slip along faults in the Front Range of Colorado in late Oligocene and younger time (Taylor, 1975; Tweto, 1975; Theobald, 1965) large enough to cause ~30° of vertical axis rotation (Mackenzie and Jackson, 1983).

The second type of deformation—moderate tilting about a near-horizontal axis—can account for the discrepancy. From 15° to 25° of west-side-down tilting about an axis oriented N15°E is required to "correct" the observed data into agreement with expected directions. This axis is perpendicular to the strike of the West Fork of the Clear Creek fault and is within 10° and 30° of strikes of the Vasquez Pass and Berthoud Pass fault zones (Figs. 1 and 2), respectively. Deformation involving dip-slip along the West Fork of the Clear Creek fault (Fig. 14)

**Figure 13. Partial equal-area projection of in situ stock (10 stocks accepted) mean and site (34 sites accepted) mean directions (solid circles) and associated projected cones of 95% confidence. Solid squares represent mid-Oligocene expected directions determined from paleomagnetic poles of Irving and Irving (1982) (I+I) and Diehl and others (1983) (D).**
may explain such tilting. With a hinge in the middle of the Red Mountain block, about 540 m of dip-slip offset along the combined Woods Creek and Berthoud Pass faults (southeast of Red Mountain and the Vasquez Pass fault to the northwest) (Fig. 14) would result in the inferred tilt. This slip estimate is in accord with Izett’s (1975) suggested upper limit of about 1 km for Neogene displacement along normal faults in north-central Colorado. We prefer a style of deformation involving variable dip-slip with offset along at least two major structures to simple dip-slip along either the Vasquez Pass or Berthoud Pass-Woods Creek faults. Dip-slip displacement along these northeast-trending structures and attending tilt would give a more northward declination for the observed Red Mountain mean direction.

Assuming that the data from the Red Mountain intrusive system record local tilting from 15° to 25° about an approximately NNE, horizontal axis, then the pre-tilt orientation of mineralizing stocks can be determined. Plunges of axes of the cylindrical Urad, Henderson, and Seriate stocks define a great circle of attitude N57°E, 66°NW. After restoring the great circle to its pre-tilt position, the orientation is N52°E, 80°NW. This trend parallels the Woods Creek strand of the Berthoud Pass fault zone, suggesting that structure controlled the emplacement of the stocks. Correcting for east-side-down tilting results in a more vertical orientation of stocks and their contacts.

Implications of 40Ar/39Ar Age-Spectrum Data for Intrusion Emplacement

The age-spectrum and magnetic polarity data provide an improved assessment of the age of intrusion, subsolidus cooling, alteration, and structural history of the Red Mountain intrusive system (Table 5), just as 40Ar/39Ar age-spectrum data on individual mineral phases of estimated isotopic closure temperatures have been used to define the subsolidus tectonothermal history of intrusive igneous rocks and associated hydrothermal deposits and regionally metamorphosed rocks in many settings (Sutter and others, 1985; Snee and others, 1988; Foster and others, 1990).

In the following discussion, we compare the Red Mountain magnetic polarity and 40Ar/39Ar isotopic age-spectrum data with published geomagnetic polarity time scales. Considerable controversy still exists about the accuracy of these polarity time scale calibrations and some calibrations are currently being revised substantially (W. A. Berggren, 1989, personal commun.). As a result, we are not able to confidently correlate magnetization polarity in the intrusive system with particular polarity chron. The durations of individual magnetozones, however, are far less controversial and have direct bearing on the interpretation of the magnetization acquisition history of the Red Mountain intrusive system.

Magnetization blocking spanned at least one field reversal following intrusion of the reversely polarized East Knob pluton and Rubble Rock stocks, possibly during cooling of the porphyry of Red Mountain. 40Ar/39Ar age-spectrum data on orthoclase from this stock indicate cooling below 350 °C possibly as early as 30.38 ± 0.09 Ma (Fig. 11A). Lamprophyre and rhyolite dikes on the surface yield 40Ar/39Ar age-spectrum data of 29.81 ± 0.10 (biotite) and 29.4 ± 0.9 Ma (orthoclase). Although we were not able to obtain 40Ar/39Ar age-spectrum data for the reversely magnetized porphyry of the East Knob pluton, the age spectrum data from the porphyry of Red Mountain provide a basis for the interpretation that the polarity reversed to normal before ca. 30 Ma. The time scale of Harland and others (1982) gives the boundary between chron 9r and chron 9 at 29.94 Ma (Fig. 15). With the exception of short polarity chron, the immediately older and younger reverse to normal transitions are placed at 31.2 and 28.3 Ma (Harland and others, 1982) and do not compare f-
Figure 15. Geomagnetic polarity time scales for late Eocene and Oligocene time compared with zircon fission-track (F-T) dates, K/Ar isotopic and $^{40}$Ar/$^{39}$Ar age-spectrum determinations for the Red Mountain intrusive system. Numbers adjacent to fission track dates and isotopic age determinations correspond to sample numbers in Table 4. Vertical lines indicate error bars; for the $^{40}$Ar/$^{39}$Ar age-spectrum data, O, B, and M refer to orthoclase, biotite, and muscovite (sericite), respectively.

Vorably with the $^{40}$Ar/$^{39}$Ar data. More recent geomagnetic polarity time scales systematically assign polarity chron to younger ages during this time period (Fig. 15) and would require cooling of the porphyry of Red Mountain during chron 11 (Montanari and others, 1988; Swisher and Prothero, 1990; McIntosh and others, 1992), possibilities which are not excluded by the argon data. According to McIntosh and others' (1992) internal calibration based on high-precision, sanidine $^{40}$Ar/$^{39}$Ar age-spectrum data from volcanic rocks, the reverse to normal transition during emplacement of the Red Mountain surface rocks would be the 11R/11 chron boundary at ca. 29.5 Ma.

Rocks at the Henderson Mine levels cooled later than those exposed at the surface. The normal polarity porphyry of Urad Mine, the deep-seated equivalent of the porphyry of Red Mountain (Carten and others, 1988), yields disturbed orthoclase and biotite age spectra of 28.0 ± 0.09 and 28.6 ± 0.3 Ma, respectively. The Henderson, Seriate, and Primos stocks, which intrude porphyry of the Urad Mine, also acquired characteristic magnetizations of normal polarity. $^{40}$Ar/$^{39}$Ar isotopic age determinations from the Seriate, Vasquez, and Ute stocks indicate that orthoclase isotopic blocking occurred between 28.5 and 28.7 Ma. Age-spectrum data on biotite (average of 27.59 ± 0.03 Ma; Table 5; Fig. 11C) specify when the central mineralized zone cooled below -280 °C. Muscovite (sericite) determinations (26.95 ± 0.08 and 27.51 ± 0.03 Ma) are younger than those of biotite, because sericite formed after the system cooled below biotite-blocking temperatures.

Whereas reverse polarity magnetizations of low coercivity and (or) low-unblocking temperature spectra are present in some samples from the subsurface rocks, we interpret the absence of reverse polarity magnetizations of high coercivity and (or) unblocking temperature to suggest that magnetization blocking occurred during one normal polarity chron, after intrusion of the Urad and Red Mountain stocks. Unblocking-temperature data support the likelihood that blocking occurred at temperatures from much higher than 500 °C to as low as 300 °C. The $^{40}$Ar/$^{39}$Ar orthoclase and biotite age spectra give estimates for a lower bound of magnetization blocking. The time between 28.5 and 28.7...
Ma is principally one of reversed polarity according to the time scales of Harland and others (1982) (chron 8R), Montanari and others (1988) (chron 9R), Harland and others (1989) (chron 9R), McIntosh and others (1992) (chron 10R), and Swisher and Prothero (1990) (chron 10R), and of normal polarity (chron 9) according to Berggren and others (1985). Although the Berggren and others’ (1985) time scale seems to match the orthoclase age-spectrum and polarity data more appropriately, we note that reverse polarity chron 8R lies between the time of orthoclase and biotite closure in this time scale in the Henderson Mine rocks. The position of normal polarity chron 8 in the time scales of Harland and others (1982) and Berggren and others (1985), chron 9 in the time scales of Montanari and others (1988) and Harland and others (1989), and chron 10 in the time scales of McIntosh and others (1992) and Swisher and Prothero (1990) is consistent with the dates for biotite closure. The general absence of reverse polarity magnetizations in the Henderson Mine rocks can be explained by emplacement before about 28.5 Ma (Table 5). The entire system cooled rapidly and magnetizations blocked to temperatures below 280 °C at about 27.6 Ma. Magnetite-sericite alteration, in particular of the Seriate stock, occurred between ca. 26.9 and 27.6 Ma. Biotite age-spectrum data tightly define cooling of the core of the mineralized system below ~280 °C at about 27.6 Ma. Magnetite-sericite alteration, in some of the underground sites may have been acquired over this time period and appear to have accurately recorded the ambient field. Comparison of the Red Mountain age-spectrum and polarity data with published geomagnetic polarity time scales fails to identify unequivocally chron in which the observed magnetizations were acquired. The likely candidates for intervals of normal polarity remanence acquisition are either Chrons 9 or 10.

CONCLUSIONS AND REGIONAL TECTONIC IMPLICATIONS

Paleomagnetic and 40Ar/39Ar age-spectrum data from most stocks of the Red Mountain intrusive system provide an improved understanding of the structural and cooling history of the suite of intrusions host to a major porphyry molybdenum deposit. Characteristic magnetizations, acquired during reverse polarity before ca. 30 Ma and normal polarity between 28.7 and 27.6 Ma, are discordant with expected directions for late Oligocene time. The discrepancy implies about 15°–25° of east-side-down tilting of the Red Mountain area about a north-northeast-trending axis and is consistent with observed field relations. The 40Ar/39Ar age-spectrum data are interpreted to indicate emplacement of surface stocks of Red Mountain before 29.85 ± 0.34 Ma (possibly before 30.38 ± 0.09 Ma). Intrusion of the Urad porphyry and the Seriate, Henderson, Vasquez, and Ute stocks, all exposed in the subsurface, occurred between ca. 28.4 and 28.7 Ma. Biotite age-spectrum data tightly define cooling of the core of the mineralized system below ~280 °C at about 27.6 Ma. Magnetite-sericite alteration, in particular of the Seriate stock, occurred between ca. 26.9 and 27.6 Ma. Magnetizations carried by maghemite in some of the underground sites may have been acquired over this time period and appear to have accurately recorded the ambient field. Comparison of the Red Mountain age-spectrum and polarity data with published geomagnetic polarity time scales fails to identify unequivocally chron in which the observed magnetizations were acquired. The likely candidates for intervals of normal polarity remanence acquisition are either Chrons 9 or 10.

Styless of local, basement-involved deformation similar to that affecting the Red Mountain area have been described by Kellogg (1973) and Hobblit and Larson (1975) for the easternmost, east-tilted flank of the Front Range. The absence of layered rocks near Red Mountain precludes directly relating tilting of area with post-middle Oligocene tectonic events in much of central Colorado and New Mexico. Early uplift and deformation along the margins of Precambrian-cored blocks in the southern Rocky Mountains of Colorado and New Mexico have been ascribed to Laramide events of latest Cretaceous to earliest Cenozoic age (Eaton, 1986; Oppenheimer and Geissman, 1989). Our interpretation of Red Mountain data indicates that blocks within the uplifted ranges were tilted at least locally in late Oligocene and younger time. Other Precambrian-cored uplifts of the southern Rocky Mountains may have been similarly deformed; the Red Mountain data should not be interpreted to indicate uniform magnitude and sense tilting of fault blocks in this part of the Front Range. In the Jamestown area (Fig. 1), about 15 km west of the eastern edge of the Front Range, Sheldon and Geissman (1983) concluded that early to mid-Tertiary stocks have been tilted only slightly during uplift. Evidence for regional, east-side-down tilting of the entire Front Range would be manifested by differential structural relief, systematic changes in metamorphic facies of Precambrian rocks, and variations in uplift ages of rocks at a constant topographic level. Variations in uplift ages were not documented by Bryant and Naeser (1980) in their fission track study in the Front Range of Colorado. Deformation in other Precambrian basement cored uplifts may be similarly complicated. Steidman and others (1989) demonstrated late Oligocene to mid-Miocene reactivation and tilting of parts of the core of the southern Wind River Mountains. Although tilting of the Red Mountain area may be in response to extension along the northern terminus of the Rio Grande Rift, the absence of layered strata precludes relating the timing of deformation to early (late Oligocene–early Miocene) or late (late Miocene and Pliocene) phases of northern Rio Grande Rift extension (Morgan and Golombock, 1984). Elsewhere in northern Colorado, there is geologic evidence for differential uplift and block faulting in Miocene and younger time (Isett, 1975; Tweto, 1980; Larson and others, 1975).

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APPENDIX: PALEOMAGNETIC AND 40Ar/39Ar AGE-SPECTRUM METHODS

At 39 sites in the intrusive system (Figs. 2 and 3), 215 samples were collected for paleomagnetic study. There were 60 samples collected from 5 intrusions at 9 sites on the surface; 155 samples were collected from 8 stocks exposed in underground workings of the Henderson Mine. The underground sites are distributed over 180 vertical meters on the 81,000-, 8,050-, 7,755-, 7,625-, and 7,500-ft levels (Fig. 3).

All samples were collected at independently oriented blocks using a magnetic compass. The intensity of NRM of most samples is <0.1 A/m. Samples on the surface of Red Mountain were collected from the
component analysis (Kirschvink, 1980) was applied to spectra of all components were
one specimen per sample was subjected to progressive ground sampling, we took azimuthal backsights to base of the least prominent outcrops to avoid the ef-
saturating inductions of -0.2 T. Samples of all intru-
susceptibility after each thermal treatment. An elec-
samples from all intrusions and consist of acquisition samples.
A check on the results of vector subtraction, principal
(Zijderveld, 1967). Directions, relative intensities, and
magnetic construction and mining equipment. Because of the intensely fractured nature of the rocks, we could not always collect seven or more samples per site.
Sites were chosen with two principal goals: (1) to sample as many separate intrusions as possible and (2) to minimize the possibility of complete thermal resetting of TRM's and isotopic ages in older stocks by progressively younger stocks. An Olivine geo-
direction is best averaged by sampling many small, rap-
idly cooled plutons, each of which might provide a record of the field during a geographically short pe-
period of time. We attempted to selectively sample pe-
meters of stocks most distant from contacts with younger stocks rather than interiors. In some places, in older stocks were intentionally sampled close to younger stocks for “contact” tests.
Block samples were drilled in the laboratory to ob-
at least three standard (11 cm) cylindrical spec-
ments and were measured using a computer-interfaced Schonstedt SSM-1A spinner magnetometer. At least one specimen per sample was subjected to progressive AF demagnetization using a Schonstedt GSD-1 single-
axis system. For information on the distribution of laboratory unblocking temperatures (Tub's) of mag-
netizations, spectrums from at least two samples per site were subjected to progressive thermal demagneti-
using a Schonstedt TSD-1 furnace. In some samples, especially for those from surface rocks, AF demagnetization to 100 mT was not enough to re-
temperatures of the specimen, and more than 5% of the NRM remained). Continued thermal treat-
ment was used to more completely isolate the rema-
ence. In general, demagnetization yielded consistent behavior characterized by linear segments, and one or more of the magnetization components could be iden-
tified using orthogonal demagnetization diagrams (Zijderveld, 1967). Directions, relative intensities, and
general coercivity/Tmax spectra of all components were determined using demagnetization diagrams, plots of normalized intensity versus demagnetization, and vec-
tor subtraction (Hoffman and Day, 1978) methods. As a check on the results of vector subtraction, principal
component analysis (Kirschvink, 1980) was applied to the demagnetization data from about 5% of the samples.
Rock magnetic tests were made on representative samples from all intrusions and consist of acquisition and backfield demagnetization of IRM, determination of Curie temperatures, and measurement of low field susceptibility after each thermal treatment. An elec-
tromagnet capable of 1.2 T inductions supplied DC inductions for IRM tests. Curie temperatures were measured using both a vertical balance (at the U.S. Geo-
Survey laboratory, Denver) and a horizontal balance (at the Univ. of New Mexico laboratory), in saturating inductions of -0.2 T. Samples of all intru-
sions were inspected with reflected light petrography to identify parageneses of viable magnetic phases.
High-precision 40Ar/39Ar age-spectrum data were obtained to define the thermal history of the intrusive system with the principal intent of quantifying the number and duration of mineralizing events. From stratigraphically known sections of drill core, 21 mus-
covite, biotite, and potassium feldspar samples used for argon thermochronology were carefully selected. Pure
geothermal separates could be extracted directly from some cores; from other cores, standard separation techniques were used to obtain pure samples. X-ray diffraction patterns of all potassium feldspars showed them to be homogeneous. All in-plane separations were un-
Aitken except one potassium feldspar from the Seriate stock that included ~10% illite formed during a later (the magnetite-sericite) alteration event.
Samples for argon analysis were irradiated in two separate groups: one in the U.S. Geological Survey Triga-A reactor and one in the University of Michigan Phoenix reactor, using normal encapsulation proce-
dures described in Snoe and others (1988). The iso-
topic composition of argon was measured at the U.S. Geological Survey, Denver, Colorado, using a Mass Analyzer Products, Limited, 215 series, rare-gas mass spectrometer. (Trade, firm, or product names are used for descriptive purposes only and do not imply an endorsement by the United States government.) Iso-
topic abundances were corrected for mass discrimina-
tion. The neutron flux monitor used in this study is hornblende MMhb-1, a sample of which is 520.4 Ma (Alexander, 1980; Sammis and Alexander, 1987); an error of 0.25% (1 sigma) was determined experimentally by calculating the reproducibility of several aliquants of argon for all mons. Samples irradiated at the University of Michigan were cor-
rected for irradiation-produced, interfering isotopes of argon by measuring production ratios for those iso-
Aitken corrected for irradiation-produced of chlorine (Roddick, 1983). Quantities of 25Ar and 39Ar were corrected for radi-
dissociative decay. Constants used in age calculations are those of Steiger and Jäger (1977). Error estimates for apparent ages of individual temperature steps were assigned by using the equations of Dalrymple and others (1981). The equations were modified to allow the option of choosing the larger of two separately derived age estimates, as prescribed by the equations of Dalrymple and others (1981) were for this reactor by Dalrymple and others (1981) were cor-
radiometric and magnetic implications of the post-Laramide, Late Eocene erosion surface in the Southern Rocky Mountains, in Curtis, B., ed., Cenozoic history of the southern Rocky Mountain Geological Society of America Memoir 144, p. 45-74. Feuillet, J. E., Gomberg, J. W., and Shidokoh, M. J., 1992, Implications of paleomagnetic data on late Cretaceous extension along the major accommoda-