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Late Paleozoic remagnetization of Precambrian crystalline rocks along the Precambrian/Carboniferous nonconformity, Rocky Mountains: a relationship among deformation, remagnetization, and fluid migration

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Abstract

Paleomagnetic and rock magnetic data and petrographic observations demonstrate that Archean to late middle Proterozoic rocks (three localities in metamorphic rocks, two in granitic plutons) in parts of the Rocky Mountains, along and below a regional nonconformity with Carboniferous strata, have acquired a secondary magnetization. This magnetization is exclusively of reverse polarity and, based on its unique direction, was presumably acquired during the Permo-Carboniferous Reverse Superchron. At most sites, the remanence is carried exclusively by hematite, although it also resides in magnetite at some localities. Based on comparison between paleomagnetic poles derived from locality mean secondary magnetizations (e.g. Decl. = 137.2°, Incl. = −18.2° $\alpha_{95} = 4.1°$, $k = 221.4$, $N = 7$ of seven samples, Archean gneiss, northern Laramie Range; Decl. = 148.7°, Incl. = −15.0°, $\alpha_{95} = 4.6°$, $k = 77.0$, $N = 14$ of 23 samples, Sherman Granite, southern Laramie Range; Decl. = 174.3°, Incl. = −18.9°, $\alpha_{95} = 6.6°$, $k = 48.6$, $N = 11$ of 13 samples, metavolcanic rocks, Sandia Mountains) and late Paleozoic reference poles for North America, this secondary magnetization does not appear to have been acquired as a direct consequence of subareal erosion prior to deposition of younger sedimentary strata. At two localities, the age of the remanence is demonstrably younger than the oldest overlying strata. Locally, the nonconformity between basement rocks and late Paleozoic strata, as well as steep shear zones within the basement rocks, may have been efficient channelways for brines flushed out of basins created during Ancestral Rocky Mountains deformation. On a continental scale, migration of fluids and attending remagnetization is consistent with epeirogenic uplift of the Pangean supercontinent and a relative lowering of ground water levels. The fact that these basement rocks do not show evidence of subsequent remagnetization during latest Cretaceous to early Tertiary (Laramide) contraction in this area suggests that the characteristics of the late Paleozoic remagnetization phenomenon were unique in time.

Keywords: remagnetization; hematite; upper Paleozoic; Ancestral Rocky Mountains; paleomagnetism

1. Introduction

One inferred consequence of migration of warm, saline fluids (brine) through Paleozoic cov-

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er strata of North America [1–3] is the acquisition of a regionally extensive secondary magnetization during late Paleozoic time. Widespread fluid migration is linked to tectonism in space and time and is inferred to have direct association with base/precious metal mineralization, petroleum accumulation, and other diagenetic processes in the U.S. mid-continent [4]. Because this secondary magnetization, found in both carbonate and detrital sedimentary rocks, appears to be of chemical origin [5,6], an association with brines, possibly as meteoric waters topographically driven from orogenic belts onto the craton, as well as evolved from deep sedimentary basins, has been postulated. Studies of fluid migration through the craton cover require a better understanding of the role of underlying basement crystalline rocks in fluid, heat, and solute transport. Although some fluid flow models assume that crystalline rocks form a relatively impermeable boundary [7], it is clear that fluid circulation through crystalline rocks can be extensive [8–11]. Limited information exists on the role of nonconformities between crystalline basement rocks and overlying strata as migration pathways (e.g. [11]. If fluids responsible for or associated with remagnetization of overlying sedimentary rocks penetrate basement rocks, chemical remagnetization of the crystalline rocks may occur.

We present paleomagnetic data from five localities in the front ranges of the central Rocky Mountains, from Wyoming to New Mexico, including the Laramie Range (Wyoming), Front Range (Colorado), and Sandia Mountains (New Mexico) demonstrating that Precambrian rocks below a regional nonconformity with Carboniferous strata have acquired a secondary magnetization of inferred late Paleozoic age. This magnetization is probably of chemical origin and we postulate that it is associated with fluid flow driven by Ancestral Rocky Mountains deformation. Notably, the secondary magnetization should not be interpreted as reflecting a single, relatively short-lived time period in the late Paleozoic. Rather, the specific age of remagnetization in the late Paleozoic probably varies widely (in a sense diachronous) from locality to locality. The pervasiveness or efficiency of remagnetization, as measured by the percent of samples having a late Paleozoic magnetization signature, varies among localities. Comparison of paleomagnetic poles derived from the observed secondary magnetizations and North American reference poles indicates that the secondary magnetization was probably not acquired in direct response to weathering. We interpret our results to suggest that the nonconformity, as well as high angle shear zones in the basement rocks, served as conduits for late Paleozoic fluid migration. The paleomagnetic data suggest a direct association between the remagnetization of crystalline rocks, Ancestral Rocky Mountains tectonism, and possible fluid migration.

2. Background and geology

During paleomagnetic studies of Proterozoic rocks in the central and southern Rocky Mountains (e.g. [12,13]), some localities were found to have well-defined magnetizations that, based on the direction (south-southeast declination and shallow, usually negative inclination) and consistent reversed polarity of the magnetizations, we infer were acquired during the Permo-Carboniferous Reverse Superchron (PCRS) [14] in the late Paleozoic. This magnetization is usually found near the nonconformity between Precambrian rocks and upper Paleozoic strata. This relationship suggests that the basement rocks were remagnetized in late Paleozoic time. To further understand the origin of this secondary magnetization, we tested the hypothesis that there is a spatial association between the nonconformity developed in the late Paleozoic and remagnetized Precambrian rocks by sampling basement rocks below well-exposed nonconformities at additional localities.

We report paleomagnetic data from five localities in rocks ranging from Archean to middle Proterozoic age in the Laramie Range, Wyoming, Front Range, Colorado, and Sandia Mountains, New Mexico (Fig. 1). We have sampled several other localities (e.g. several exposures of the Neoproterozoic Sandia Granite at the nonconformity below lower Pennsylvanian strata in the Sandia Mountains, east of Albuquerque; metamorphic

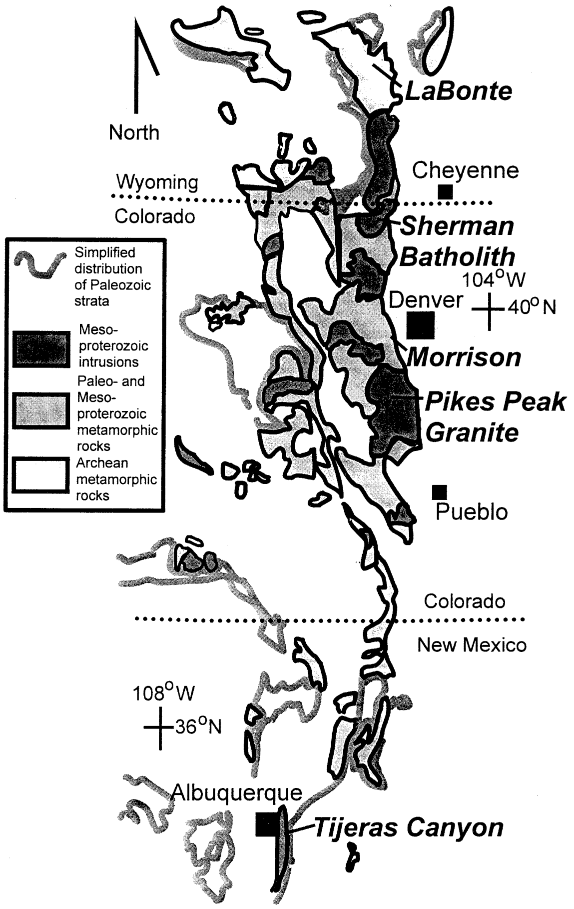

Fig. 1. Simplified geologic map showing distribution of Precambrian crystalline rocks and upper Paleozoic strata in part of the Central and Southern Rocky Mountains, western USA. All paleomagnetic sampling localities referred to in the text are indicated.

rocks exposed at the nonconformity below Jurassic strata in the Black Canyon, Gunnison River area, central Colorado) but no coherent magnetizations, of any age, have of yet been identified. The principal reason is that the magnetic mineralogy of these rocks is dominated by very low coercivity magnetite. This area was subject to extensive erosion and uplift from late Mississippian through Pennsylvanian time, during Ancestral Rocky Mountains contractional deformation [15–18]. From middle Pennsylvanian to late Permian time, thick sequences of predominantly detrital sediments accumulated in major basins adjacent to uplifts [17], creating a regionally extensive nonconformity between Precambrian rocks and Carboniferous to lower Permian strata. The regional stratigraphy indicates that deformation ceased by earliest Triassic time. Beginning in the latest Cretaceous and continuing into the Neogene, the area was uplifted and eroded during the Laramide orogeny and subsequent extension, offsetting and tilting nonconformities between Precambrian and Paleozoic strata.

Geologic relations differ at each of the five localities examined. At the northern Laramie Range locality (Fig. 1), Archean gneiss is cut by a northeast-trending mafic intrusion known as the La Bonte Gabbro [19]. The gneiss and gabbro are overlain by upper Devonian to lower Permian sandstones and carbonate rocks [20]. Farther south, the Sherman batholith localities include five sites in different phases of the 1.4 Ga Sherman Granite (SG) [21]. These sites crop out along a nonconformity that dips gently (less than 10°) to the east at and near the Colorado/Wyoming border (Fig. 1). One site at this locality (SG5) includes a regolith breccia overlain, less than 250 m to the southeast, by nearly flat to gently east-dipping Pennsylvanian Fountain Formation strata. Near Denver, the Morrison (roadcut) locality (Fig. 1) includes, a few meters below the unconformity, a vertical thickness of about 30 m of schist and gneiss regionally metamorphosed in late early and middle Proterozoic time [22]. At this locality, the oldest strata above the nonconformity are medium- to coarse-grained, hematite-cemented detrital rocks of the Pennsylvanian Fountain Formation [17]. The Pikes Peak locality (Fig. 1) includes several sites spaced over about 5 km along Colorado Highway 126, near Pine, CO, in the northern part of the 1.09 Ga Pikes Peak batholith [23] in the Front Range. In this area, upper Paleozoic strata, if originally present, were completely eroded during latest Cretaceous/early Tertiary uplift and the distance to the nonconformity is unknown. At the Tijeras locality in the Sandia Mountains of New Mexico (Fig. 1), metavolcanic rocks of the Tijeras greenstone [24] are overlain by arkoses of the Atokan Sandia Formation.

At the northern Laramie Range locality, two sites at the Sherman Granite locality, the Tijeras locality, and the Morrison locality we determined the attitude of the nonconformity by three-point method and/or using bedding plane attitudes in immediately overlying or nearby strata. Structural corrections to the paleomagnetic data from these localities were applied using simple back-tilt about present strike (Table 1). No structural correction was applied to data from the other Sherman Granite sites or the Pikes Peak locality. Based on regional geologic relations, however, the maximum tilt correction that could be applied for all Sherman Granite results is less than 5°.

3. Paleomagnetism

3.1. Sampling and laboratory methods

All samples were collected from roadcut or natural surface exposures using a portable drill. Where possible, samples were oriented using both magnetic and sun compasses. Remanence measurements were made using a three-axis superconducting rock magnetometer. Progressive demagnetization involved thermal or a combination of alternating field (AF) then thermal treatment. We monitored bulk susceptibility during thermal

Table 1
Paleomagnetic data from selected Proterozoic rocks, central Rocky Mountains

Site	Strike/dip	Decl.$_{is}$	Incl.$_{is}$	Decl.$_{sc}$	Incl.$_{sc}$	N/N_o	α_{95}	k	α_{95}1–3	α_{95}1–2	*P*lat. (°N)	*P*long. (°E)	$\delta p/\delta m$
Archean gneiss, northern Laramie Range (42.45°N, 105.50°W)													
LB3	332°/20°	137.2°	−18.2°	144.5°	−22.1°	7/7	4.1°	221	2.7°	3.8°	46.3°	130.0°	2.3/4.3
Sherman Granite, southern Laramie Range (41.00°N, 105.00°W)													
LA41		147.3°	−15.2°			2/9							
LA42		156.0°	−15.0°			1/9							
SG1,2		166.9°	−18.1°			3/13							
SG5	359°/08°	148.7°	−15.0°	150.8°	−18.9°	14/23	4.6°	77	3.8°	4.5°	49.5°	122.7°	2.5/4.8
SGPZ2	359°/08°	147.1°	−12.8°	148.9°	−16.9°	4/10	13.6°	46	6.6°	10.8°	47.5°	124.1°	7.1/13.9
Mean		154.9°	−16.0°			5	9.7°	91			50.4°	115.7°	5.1/10/0
Mean		∼148°	∼-14°	∼150	∼-18	2	∼9	-			∼48	∼123	
Proterozoic gneiss, Morrison, CO (39.50°N, 105.50°W)													
MR1	350°/30°	151.0°	16.8°	145.4°	5.4°	24/28	4.7°	41	3.8°	4.9°	37.2°	119.9°	2.4/4.7
Pikes Peak Granite, Front Range of Colorado (39.25°N, 105.25°W)													
PP100		170.2°	−19.6°			9/9	5.9°	78	2.5°	6.6°	59.8°	94.5°	3.2/6.1
PP101		168.0°	−22.4°			10/10	3.2°	229	1.7°	3.6°	60.6°	99.6°	1.8/3.4
PP4 pz		154.0°	−21.4°			10/9	8.4°	33	4.4°	9.9°	53.6°	121.2°	4.7/8.9
PP4 pc		279.5	38.1			8/9	7.9°	50	5.5°	7.5°			
PP102		291.0	28.4			11/11	5.7°	64	4.2°	5.7°			
PP110		157.7	−15.7			11/11	9.0°	26	3.8°	10.3°	53.2°	113.4°	4.8/9.3
PP113		156.2	−21.0			9/9	3.6°	202	2.1°	3.8°	54.9°	118.1°	2.0/3.8
Mean		161.2	−20.1			5	7.0°	121			56.6°	109.9°	3.8/7.3
Tijeras greenstone, Sandia Mountains, New Mexico (35.05°N, 106.35°W)													
TC10	355/29	164.7°	−16.0°	174.3°	−18.9°	11/14	6.6°	49	6.6°	8.9°	64.1°	86.6°	3.6/6.9

Strike/dip, value of strike is 90° clockwise from dip direction; Decl.$_{is}$ and Incl.$_{is}$ are declination and inclination of the in situ site mean direction; Decl.$_{sc}$ and Incl.$_{sc}$ are declination and inclination of the site mean directions after application of tilt corrections, where appropriate; N/N_o is ratio of samples used in the calculation of the site mean direction to the total number of samples collected and measured; α_{95} is semi-angle of the cone of 95% confidence about the site mean direction; k is precision parameter (Fisher, 1953); *P*lat. and *P*long. are the latitude and longitude of the virtual or mean paleomagnetic pole; the value of the paleomagnetic pole listed in the table is based on the tilt-corrected site mean direction, where appropriate; $\delta p/\delta m$ and the minor and major semi-axes of the 95% confidence region, in degrees, about the paleomagnetic pole.

demagnetization for most of the samples analyzed.

Several rock magnetic experiments were performed to characterize the magnetic mineralogy of samples containing the southeast and shallow magnetization. In addition, we expected to be able to use rock magnetic data as well as petrographic observations to discriminate, at least for some of the localities, between samples containing the southeast and shallow magnetization and those that did not. The experiments included acquisition of isothermal remanent magnetization (IRM), utilizing an impulse-type direct current magnet, backfield direct current demagnetization of IRM, and AF demagnetization of anhysteretic remanent magnetization (ARM), saturation IRM (SIRM) and NRM. In some cases, these tests do not offer an obvious means by which to discriminate between rocks having the late Paleozoic remanence and those having only a preexisting, possibly primary remanence. For materials from some localities, we collected hysteresis data on the alternating gradient force magnetometer at the Institute for Rock Magnetism, University of Minnesota.

3.2. Paleomagnetic data

To generalize, at each of the five localities, demagnetization isolated a similar magnetization, of south-southeast declination and shallow, usually negative, inclination (Figs. 2, 3, 4, 6 and 7). This magnetization is common to basement rocks of distinctly different ages, strongly suggesting that it is a secondary magnetization. Further, at some localities, previous studies have demonstrated primary magnetizations, consistent with the age of the rocks [12,27]. As noted above, the percentage of samples giving this magnetization varies (Table 1). At some localities, other magnetizations are resolved. We briefly discuss demagnetization results from each locality, in geographic order from north to south. Our discussion of magnetizations isolated in these rocks refers to directions in in situ coordinates.

Natural remanent magnetization (NRM) directions for gneiss samples at the northern Laramie Range locality are of southwest declination and moderate to shallow positive inclination. NRM intensities of these rocks range from 2.0 to 8.2 mA/m, with an arithmetic mean of 5.9 mA/m. Two components of magnetization are resolved in most samples. Although poorly grouped at the locality level, the first magnetization isolated is of southwest declination and moderate positive inclination revealed by laboratory unblocking temperatures below about 350°C and peak AF values up to about 100 mT (Fig. 2a). Magnetite is the principal carrier of this magnetization. A southeast declination, shallow negative inclination magnetization is isolated above about 350°C (Fig. 2a) and most of this magnetization is unblocked over a temperature range above 600°C, consistent with hematite as the principal carrier. At this locality, we also sampled the cross-cutting La Bonte Gabbro [19] less than 50 m from the site in gneiss. In these rocks, the only magnetization identified is of east-northeast declination and steep positive inclination, with a magnetization residing entirely in magnetite (Fig. 2b, c).

Samples from the Sherman Granite locality yield complex results. At four sites (LA41, LA42, SG1, SG2) in the central part of the Sherman Granite in the southern Laramie Range, less than a third of the samples collected yield southeast and shallow magnetizations (Fig. 3a). In these samples, the magnetization is fully isolated over a temperature range above 500°C. Most samples from these four sites contain a magnetization, residing in magnetite, that is of northeast (or southwest) declination and moderate negative (or positive) inclination. We interpret this remanence to be a thermoremanent magnetization of 1.4 Ga age [12]. At site SG5, collected just below the nonconformity, the southeast and shallow magnetization is isolated in 14 of 23 samples (Fig. 3b). The NRM intensities of these rocks range from 0.24 mA/m to 64.2 mA/m, with an average of 7.7 mA/m. In some samples, this southeast declination magnetization is partially isolated by AF demagnetization (Fig. 3c), indicating that magnetite carries much of the remanence. In most samples, the magnetization has a distributed unblocking temperature spectrum up to 680°C, consistent with hematite as the principal magnetization carrier (Fig. 3d). A few samples

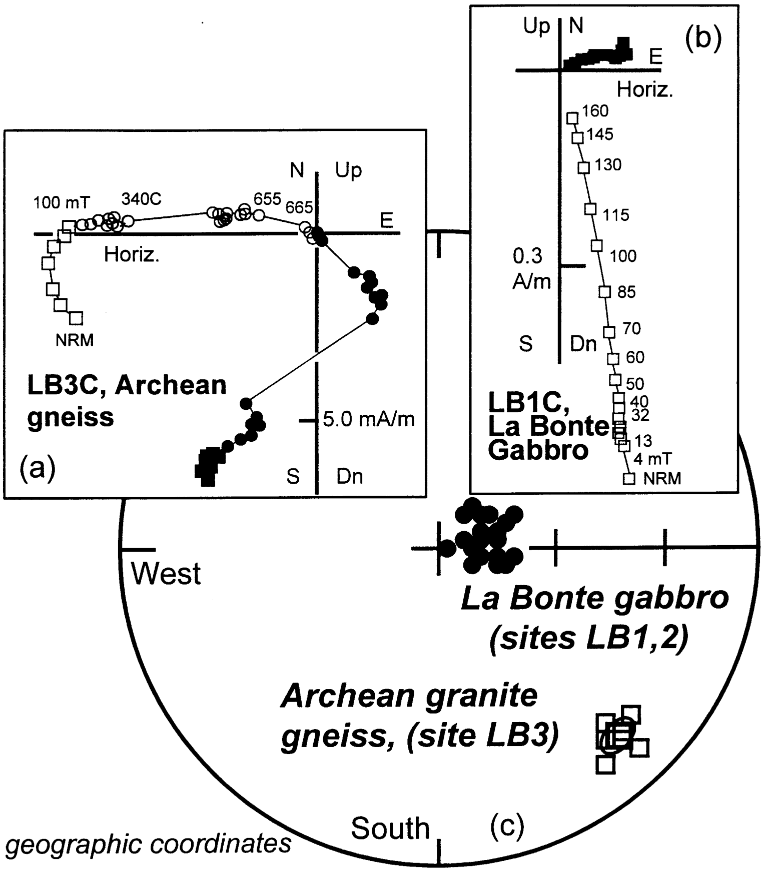

Fig. 2. Summary of paleomagnetic data from the La Bonte locality, including modified orthogonal demagnetization diagrams [25,26] showing the endpoint of the magnetization vector projected onto orthogonal horizontal and true vertical planes (a, b) and an equal area projection of directional data, including the site mean for LB3 (Archean gneiss) and the La Bonte Gabbro, with associated α_{95} cones of confidence (c). Open (closed) symbols refer to projections on the upper (lower) hemisphere.

yield a magnetization of north declination and moderate positive inclination, similar to that of the present-day field, but the presence of this magnetization is not pervasive. Unlike other sites in the Sherman Granite, none of the SG5 samples reveal a northeast declination, moderate negative inclination (or antipode) magnetization. Site SGPZ2, about 1 km west of site SG5, consists of two small, sub-circular low-relief outcrops less than 20 m apart. Four samples from one outcrop consistently yield a magnetization of southeast declination and shallow inclination (Fig. 3e); the NRM intensities of these samples range from 0.8 to 1.8 mA/m, with an average of 1.3 mA/m. However, six samples from the other outcrop yield dispersed, low coercivity magnetizations. We have calculated two mean directions for the Sherman Granite locality. The first gives equal weight to the results from five sites (SG1 and SG2 combined); the second is less biased and is provided by results from only sites SG5 and SGPZ2, from which the majority of the data were obtained.

At Morrison, schist and gneiss samples that contain the secondary magnetization have NRM directions that range from north and moderate positive to southeast and shallow positive inclinations. The NRM intensities of these rocks range from 0.74 mA/m to 5.6 mA/m, with an average of 3.1 mA/m. A southeast and shallow remanence is

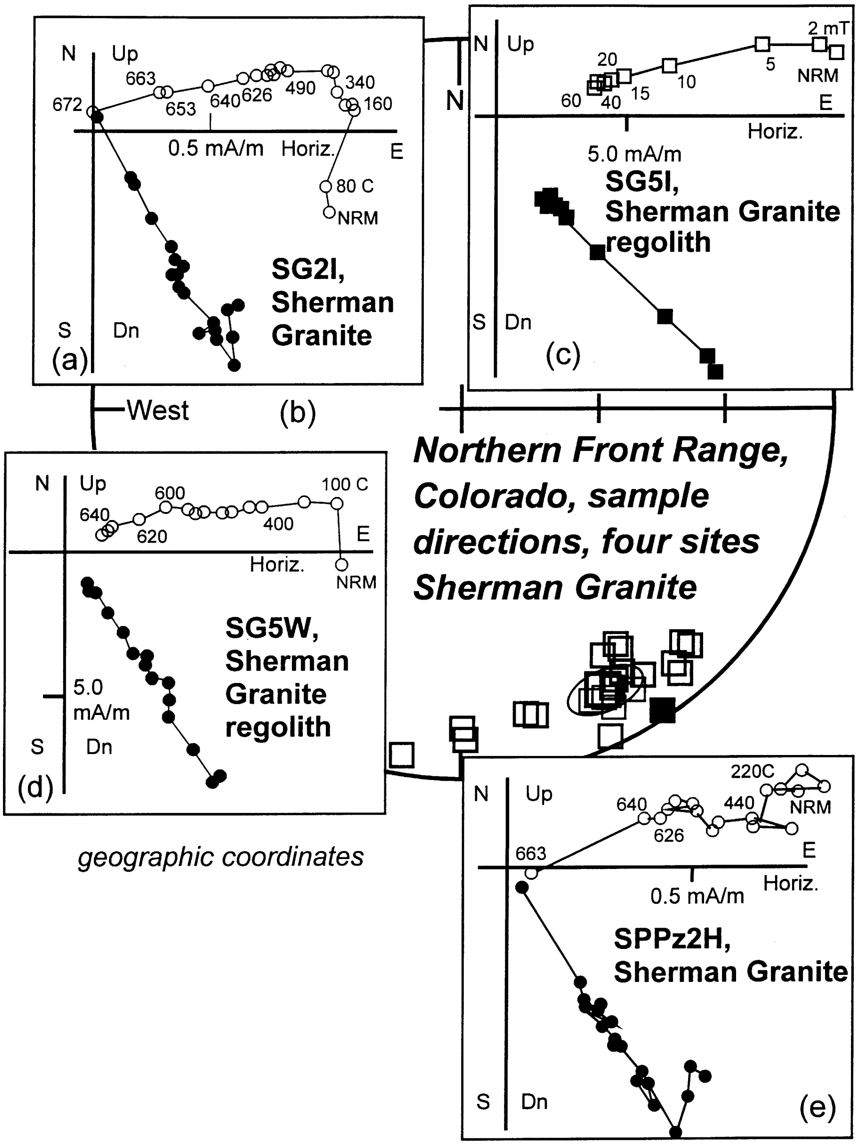

Fig. 3. Summary of paleomagnetic data from the Sherman Granite locality, including modified orthogonal demagnetization diagrams (a, c–e) and an equal area projection of directional data, including a locality mean based on data from four sites and the associated projected α_{95} cone of confidence (b). Open (closed) symbols refer to projections on the upper (lower) hemisphere.

the principal magnetization isolated in these rocks and is typically unblocked between 400 and 680°C (Fig. 4a–c). In some samples, two distinct southeast-directed magnetizations are present (e.g. sample MR1Q, Fig. 4a) and the higher unblocking temperature remanence is always of shallower inclination. With the exception of samples from the Tijeras Canyon locality (below), samples from the Morrison locality exhibited the greatest changes in magnetic susceptibility with progressive thermal demagnetization (Fig. 5); the changes range from subtle to modest increases (up to a factor of four) in susceptibility. At this locality, the well-exposed nonconformity with upper Paleozoic strata dips 30° to the east. In rocks exposed more than about 30 m below the nonconformity, the

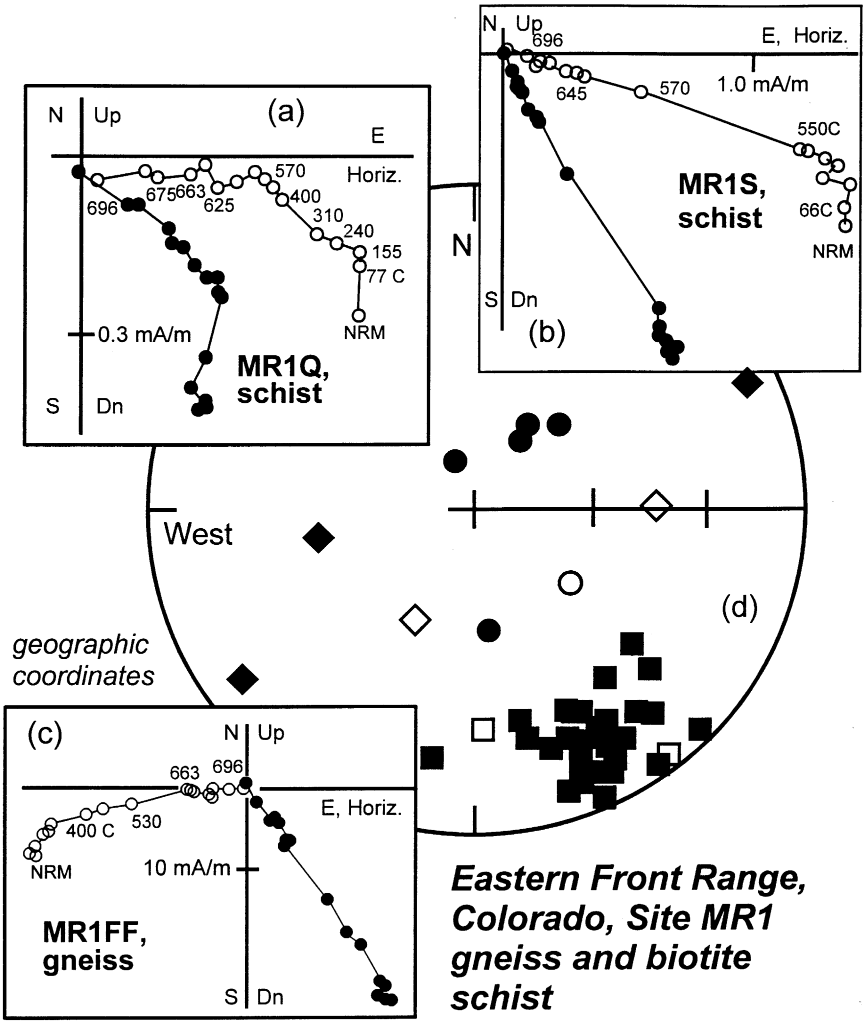

Fig. 4. Summary of paleomagnetic data from the Morrison locality, including modified orthogonal demagnetization diagrams (a–c) and an equal area projection of directional data; squares represent directions of secondary magnetizations, diamonds represent normals to remagnetization circles, for samples with secondary magnetizations, and circles are directions of magnetizations carried by magnetite in fresh schist and gneiss. Open (closed) symbols refer to projections on the upper (lower) hemisphere.

remanence is dominated by magnetite, the southeast and shallow remanence is not present, nor could any other coherent magnetization be identified in these rocks.

Sites in Pikes Peak Granite yield somewhat different, but internally consistent results. Sites PP100 and PP101, about 3.5 and 0.9 km north of Pine, CO, respectively, have NRM intensities ranging from 3.2 to 14.1 mA/m, with an average of 6.6 mA/m. The average bulk susceptibility values for sites PP100 and PP101 are 3.5×10^{-4} and 4.8×10^{-4} (SI volume), respectively, with standard deviations of 0.8×10^{-4} and 1.3×10^{-4} (SI volume), respectively. For some samples at each site, magnetizations are dual component in character. AF demagnetization identifies a moderately well-grouped magnetization of northwest to west declination and moderate positive inclination, comprising about a third of the NRM (Fig. 6a). Subsequent thermal demagnetization of AF demagnetized specimens, beginning at temperatures greater than about 200°C, isolates a well-defined southeast declination and shallow negative inclination magnetization up to 680°C, although most samples decrepitated at temperatures above about 550°C. Other samples contain a single component magnetization of southeast declination and shallow inclination that is unblocked up to about 680°C. All samples from site PP4, about 1.2 km south of Pine, yield uniform, multicomponent behavior. AF demagnetization identifies a well-defined and well-grouped west and moderate positive inclination magnetization comprising over 50% of the NRM (Fig. 6b, c). Thermal treatment of AF demagnetized specimens, particularly over temperatures between 550 and 680°C, isolates a well-defined southeast declination and shallow negative inclination magnetization (Fig. 6b, c). NRM intensities at this site range from 1.7 to 6.5 mA/m, with an average of 3.8 mA/m. Site PP102, 1.4 km south of Pine, on the other hand, yields only a single component NRM and the magnetization isolated in AF demagnetization is of west-northwest declination and moderate positive inclination (Fig. 6d). NRM intensities for this site range from 117 to 21 mA/m, with an average of 61 mA/m. The average bulk susceptibility for samples from this site is 11.2×10^{-4} (SI volume) with a standard deviation of 3.2×10^{-4} (SI volume). Demagnetization results from this site show no evidence for secondary late Paleozoic magnetization. In the nearby area, other sites (e.g. 110 and 113, both in a more aplitic phase of the Pikes Peak Granite) contain a well-grouped secondary late Paleozoic magnetization. The average bulk susceptibility values for these sites are lower, with values of 5.8×10^{-5} and 5.5×10^{-5} (SI volume), respectively, with standard deviations of 1.6×10^{-5} and 1.8×10^{-5} (SI volume), respectively.

From the Tijeras locality, 15 samples were collected in a 2-m thick zone of oxidized metavolcanic rock below Sandia Formation strata, which dip about 30° southeast. NRM directions are well-grouped with south-southeast declinations and shallow negative inclinations (Fig. 7b). NRM intensities for these rocks range from 0.7 to 5.7 mA/m, with an average of 1.5 mA/m. The principal magnetization in these rocks is unblocked above temperatures greater than 400°C. Above about 620°C, however, demagnetization behavior becomes erratic, with substantial increases in magnetization intensity (Fig. 7a), suggesting the growth of new magnetic phases during thermal treatment. For these samples, we could not conclusively demonstrate that the magnetization would fully decay to the origin. Nonetheless, anchored line segments fit to demagnetization data between about 580 and 620°C are well-grouped and are of southeast declination and shallow negative inclination (Fig. 7b).

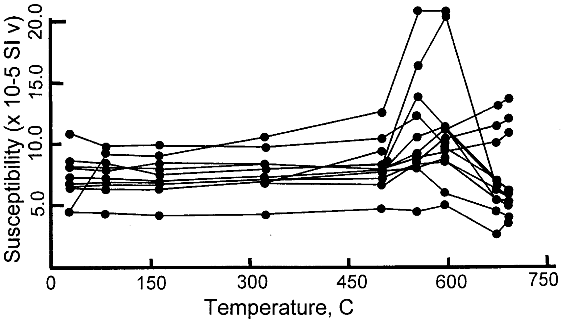

Fig. 5. Plot of bulk susceptibility vs. temperature for selected samples of Proterozoic gneiss, Morrison area, subjected to progressive thermal demagnetization. All samples shown contain a secondary, late Paleozoic magnetization.

3.3. *Rock magnetic data and petrographic observations*

For samples containing the southeast and shallow magnetization, rock magnetic data and petrographic observations show that the magnetic mineralogy is dominated by hematite. However, on the basis of demagnetization behavior, hematite does not always carry most of the remanence (e.g. Fig. 3b). For samples containing the secondary, late Paleozoic remanence, usually carried in hematite, IRM acquisition curves do not saturate by 1.3 T (Fig. 8b, d, f). The presence of minor amounts of magnetite is indicated by inflections in the curves at about 0.1 T; because IRM values are less than 20% of the maximum reached at 1.3 T, magnetite must be very subordinate in volume relative to a higher coercivity phase. Hysteresis data (Fig. 9) for individual potassium feldspar grains from samples at three sites in the Pikes Peak Granite are further consistent with the pres-

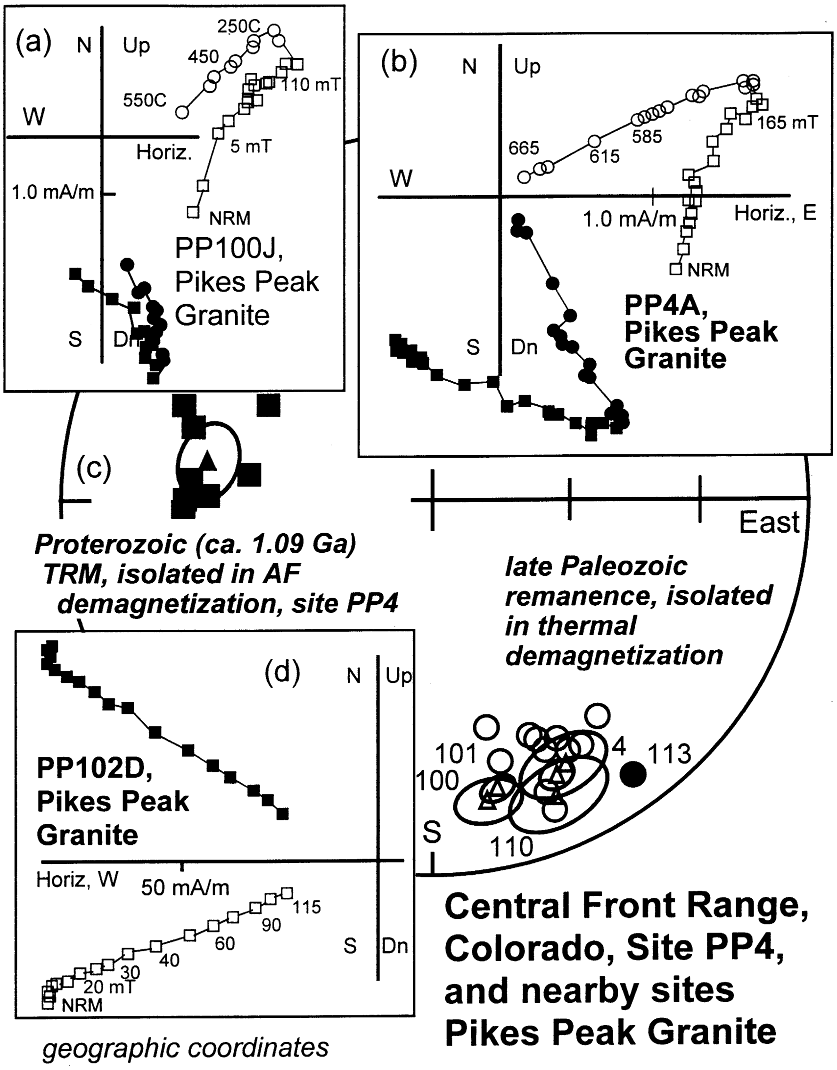

Fig. 6. Summary of paleomagnetic data from the Pikes Peak Granite locality, including modified orthogonal demagnetization diagrams (a, b, d) and an equal area projection of directional data (c), with squares representing the Proterozoic, magnetite-carried magnetization and circles the secondary, hematite-carried magnetization, including site mean directions and associated projected α_{95} cones of confidence, for the Proterozoic magnetization at site PP4 and the secondary, late Paleozoic magnetization at several sites. Open (closed) symbols refer to projections on the upper (lower) hemisphere.

ence of a high coercivity phase mixed in the feldspars, to different degrees, with a phase of lower coercivity.

For the Sherman Granite, Pikes Peak Granite, and Morrison localities, we compare rock magnetic observations from samples containing the secondary, late Paleozoic magnetization, with those from nearby localities where, by comparison with other paleomagnetic data [12,27], either a magnetite-dominated thermoremanent magnetization is the principal component (Sherman Granite and Pikes Peak Granite) or a magnetite-dominated yet low coercivity, dispersed magnetization characterizes the rocks (Morrison schist and gneiss). For Sherman Granite and Pikes Peak Granite samples with a magnetite-dominated

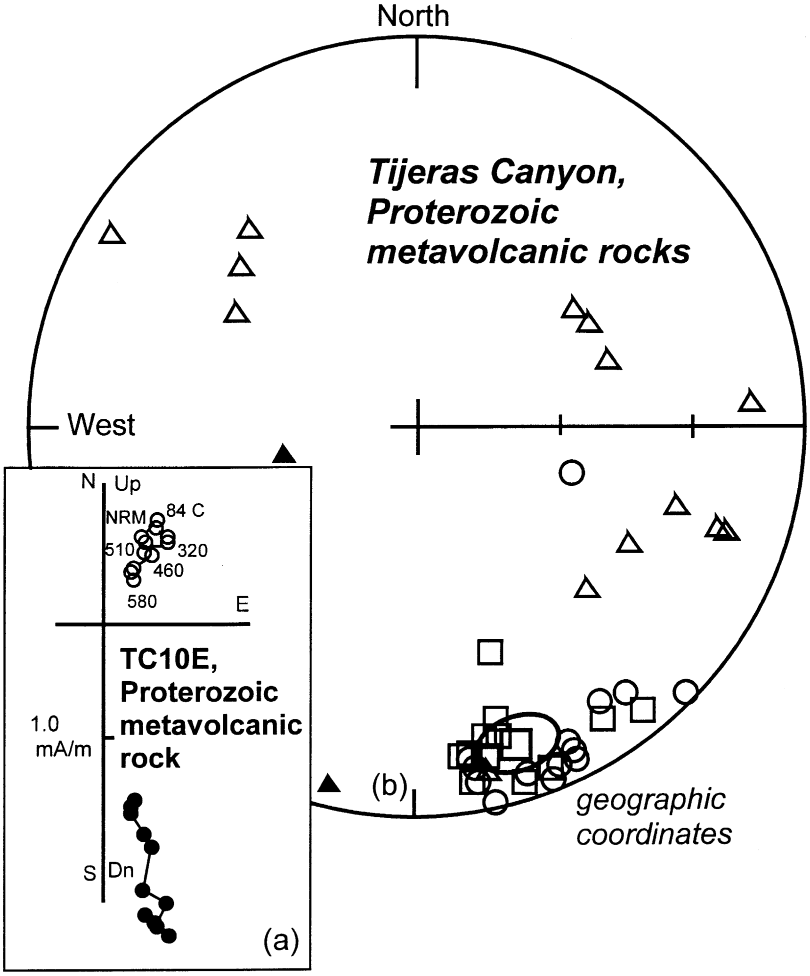

Fig. 7. Summary of paleomagnetic data from the Tijeras Canyon locality, including modified orthogonal demagnetization diagrams (a) and an equal area projection of directional data (b), with circles showing NRM directions for samples containing the secondary magnetization, upright triangles the directions of magnetizations carried in magnetite and isolated in metavolcanic rocks that do not contain the secondary magnetization, and squares the directions of magnetizations partially isolated (see text) in samples containing the secondary magnetization, including the site mean direction for the secondary, late Paleozoic magnetization and associated projected α_{95} cone of confidence. Open (closed) symbols refer to projections on the upper (lower) hemisphere.

TRM (e.g. samples LA42Ha, PP14C, Fig. 8a, e), IRM acquisition data show that hematite is an abundant magnetic phase, despite demagnetization data showing that hematite does not carry a discernible late Paleozoic remanence; in AF demagnetization of these rocks, over 90% of the magnetization is removed by 120 mT. Notably, there is significant difference in NRM intensities between sites that contain a well-defined late Paleozoic remanence (e.g. PP4) and those that contain, as the major remanence, a primary magnetization carried in magnetite (e.g. PP102, with NRM intensities at least an order of magnitude higher). Bulk susceptibility data suggest that samples from site PP102 have higher concentrations of magnetite than those from sites PP100 and PP101. Notably, sites PP110 and PP113, containing only a secondary magnetization, have bulk susceptibilities that are about an order of magnitude lower than sites PP100 and PP101. Hystere-

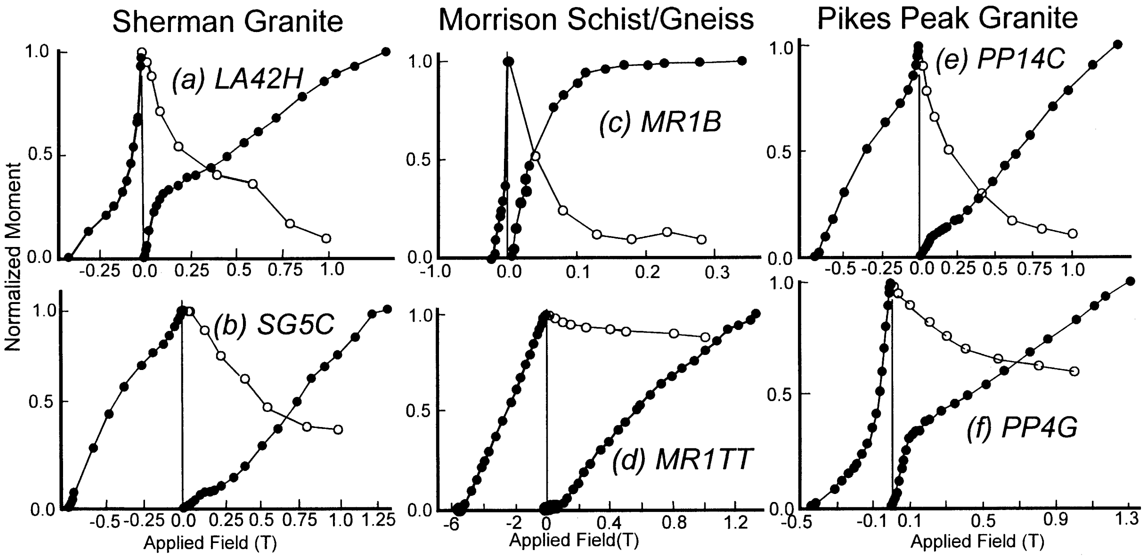

Fig. 8. Rock magnetic data for samples from the Sherman Granite, Morrison, and Pikes Peak localities. For each sample, solid circles show the acquisition of isothermal remanent magnetization (IRM) and backfield demagnetization of IRM acquired at peak fields of 1.3 T. Open circles show the AF demagnetization of anhysteretic remanent magnetization (0.1 mT field acquired in a peak alternating field of 99 mT).

sis response by the potassium feldspar grain from sample PP102F differs from that from feldspars at sites PP100 and PP101, in that the hysteresis curve is more constricted at relatively low applied fields, implying, in a general sense, a greater contribution by a low coercivity phase (e.g. magnetite), which is consistent with demagnetization response at this site (Fig. 6d). In contrast, magnetite is the dominant magnetic phase in gneisses at the Morrison locality that do not contain the secondary, late Paleozoic magnetization (Fig. 8c). Overall, these observations are interpreted to suggest that hematite formation in crystalline rocks, regardless if they contain a secondary magnetization, may not have been restricted to the late Paleozoic, when a well-grouped magnetization, in hematite, was clearly acquired in some of the rocks. Nonetheless, the stabilization of a secondary, late Paleozoic remanence carried by hematite in some crystalline rocks must have been a unique process in their history.

Petrographic observations reveal that hematite exhibits several textural relations in these rocks (Fig. 10), in part because of the diverse types of rocks that have yielded this secondary magnetization. Two common occurrences of hematite are as veins of fine-grained translucent to coarser, opaque (specularite) grains (Fig. 10A, B) and as minute, crystallographically oriented grains in both plagioclase and potassium feldspars (Fig. 10C, D); these are best displayed in granitic rocks from the Sherman Granite and Pikes Peak sites. For the La Bonte, Sherman Granite, and Pikes Peak localities, magmatic magnetite grains are only moderately oxidized. At the Sherman Granite site SG5, veins of specular as well as finer-grained translucent hematite, containing breccia fragments of silicate grains, cut intact granite (Fig. 10E, F).

4. Discussion

In general, the in situ and, where possible, structurally corrected paleomagnetic data from the five localities yield paleomagnetic poles (Table 1, Fig. 11) that are unlike those of Proterozoic age for North America. Notably, the poles obtained are distinctly different from those representative of ages of intrusion (e.g. the ca. 1.45 to 1.40 Ga

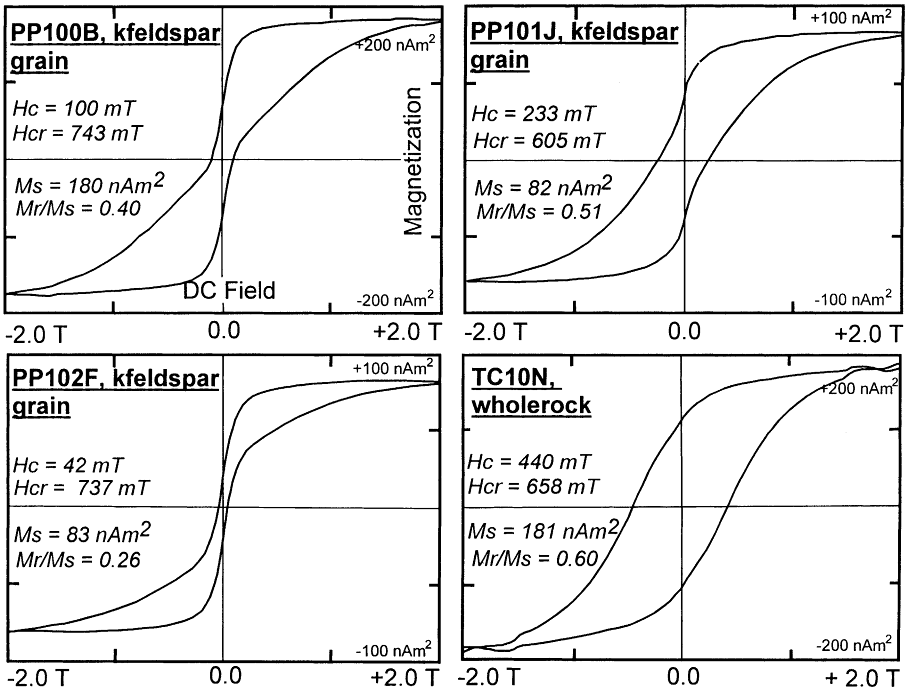

Fig. 9. Examples of hysteresis curves (slope-corrected) for potassium feldspar crystals from samples from three sites in the Pikes Peak Granite, all referenced in the text, and whole rock material in a sample from the site in fine-grained metavolcanic rock in Tijeras Canyon, also referenced in the text. For each paleomagnetic sample, at least 10 crystals or whole rock pieces were run for hysteresis curves; the behavior of all of the specimens from each sample is very similar.

time period) or regional metamorphism. They are similar, overall, to those of late Paleozoic age [28–31] and because of this similarity and their exclusively reversed polarity, the magnetizations identified at each locality are consistent with acquisition during the PCRS. For most localities, complete unblocking of the late Paleozoic remanence over a range of temperatures above 600°C implies that hematite is the dominant carrier of remanence. For some samples from site SG5 in the Sherman Granite, however, a relatively low coercivity phase (either magnetite or maghemite) carries some of this secondary remanence. Overall, we suggest that this secondary magnetization is a chemical remanence acquired at low (less than 200°C) temperatures and that the mechanism for remagnetization is likely similar to that affecting Precambrian crystalline rocks and overlying upper Cambrian Reagan Sandstone in the Arbuckle Mountains, which were also remagnetized in the late Paleozoic [32]. The absence of any documented magmatism of late Paleozoic age throughout the study area [33] supports this interpretation.

In the context of a more complete understanding of the late Paleozoic remagnetization, the additional well-defined and well-grouped magnetizations at some of the localities require explanation. The east-southeast and steep positive inclination magnetization (after structural correction) from the La Bonte Gabbro is carried by high coercivity magnetite and is unlike expected Phanerozoic magnetizations for North America. We speculate that this magnetization may be a primary TRM of early Mesoproterozoic age (ca. 1.7–1.6 Ga), although this is not known with certainty. Regardless of the exact age of the gabbro's magnetization, this rock, less than 20 m from our site in Archean gneiss, was not remagnetized in late Paleozoic time.

For Sherman Granite sites collected in the central part of the batholith, the principal magneti-

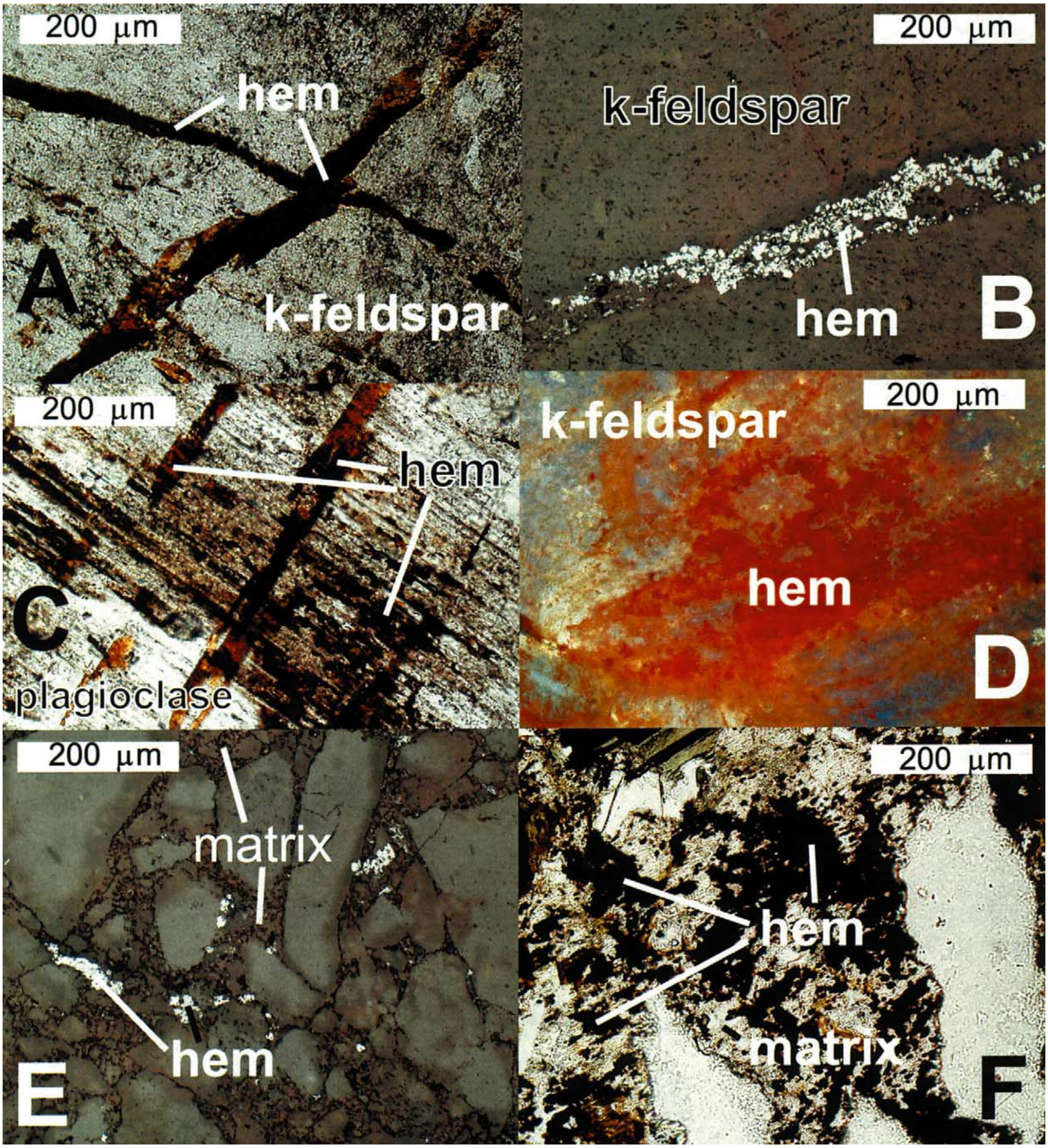

Fig. 10. Photomicrographs showing hematite parageneses in remagnetized granitic rocks of the Pikes Peak Granite and Sherman Granite. In each photomicrograph, the scale bar is 200 μ. (A) Hematite-filled veins cutting potassium feldspar, transmitted light (sample PP4A). (B) Hematite-filled veins cutting potassium feldspar, reflected light (sample PP4A). (C) Partial replacement of plagioclase feldspar by hematite, transmitted light (sample PP4A). (D) Fine-grained hematite replacing potassium feldspar, transmitted light, crossed polars (sample SG5F). (E) Hematite in matrix material of brecciated Sherman Granite, reflected light (sample SG5V). (F) Hematite in matrix material of brecciated Sherman Granite, transmitted light (sample SG5V).

zation in the three northern sites, of northeast declination and moderate negative inclination, is carried by magnetite. This magnetization is probably a TRM acquired during the initial, relatively rapid cooling of the Sherman Granite following emplacement at ca. 1.41 Ga [12]. The irregular distribution of the secondary, late Paleozoic magnetization in the Sherman Granite indicates that the mechanism that caused remagnetization was heterogeneous in its effectiveness.

The paleomagnetic data from the Pikes Peak locality are remarkable. At two sites, all samples contain both a west-northwest and moderate positive inclination magnetization carried in magnetite and the late Paleozoic secondary magnetization, of nearly identical intensity, carried in hematite. Because of its similarity with previously reported paleomagnetic data [27], the magnetite-dominated magnetization is probably a primary TRM acquired at about 1.09 Ga. In this case, because of the preservation of a TRM in magnetite, the primary magnetization is identified at low to moderate coercivities in AF demagnetization, whereas the secondary magnetization is isolated at higher temperatures.

The inclination of the well-grouped hematite-dominated magnetization in schist and gneiss at the Morrison locality is steeper (+17°, in situ; +5°, corrected for the tilt of the unconformity) than expected for a late Paleozoic magnetization, as the inferred paleolatitude for this part of North America remains nearly constant from the late Pennsylvanian through the early Triassic. We doubt that the tilt correction that we applied is in error (i.e. unrecognized component of plunge) because the orientation of the nonconformity remains constant for several tens of kilometers along the eastern flank of the Front Range at this latitude. Although the magnetization may be older than late Paleozoic, the uniform reverse polarity of the remanence, the similarity between the observed declination and that expected for late Paleozoic time, and spatial relationship between the rocks with this secondary magnetization and the late Paleozoic nonconformity makes us doubt that this is the most logical explanation for the observed discordance. Over the area sampled at this locality, metamorphic rocks exhibit a uniform, strongly developed foliation of about 039°/44°, at an angle of about 15–20° with the unconformity and overlying strata. As described above, biotite, which largely defines the fabric in these rocks, is partially replaced by specular hematite. Although we have not rigorously evaluated by collecting anisotropy of magnetic susceptibility data, it is possible that the direction, and more specifically inclination in this case, of the secondary magnetization is controlled by the strong foliation [34]. Deflection of the remanence into the foliation plane could explain the discrepancy between observed and expected incli-

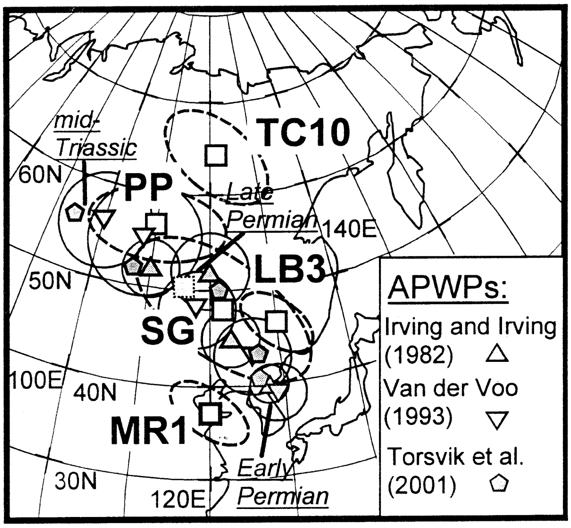

Fig. 11. Orthographic global projection showing the late Paleozoic to earliest Mesozoic apparent polar wander path (APWP) compilations for North America. Poles from remagnetized Precambrian crystalline rocks, with associated cones of 95% confidence (dashed lines), shown as large, lightly filled squares (corrected for tilt of strata, nonconformity, where appropriate) (LB3, northern Laramie Range; SG, Sherman Granite; MR1, Morrison; PP, Pikes Peak Granite; TC10, Tijeras Canyon). The square with the dashed outline is that based on data from all five sites at the Sherman Granite locality. Reference poles for North America from Irving and Irving [30] shown as upright triangles (with α_{95} values), Van der Voo [28] as inverted triangles (with α_{95} values), and Torsvik et al. [31] as pentagons (α_{95} values not shown, given similarity of values with those of Van der Voo [28]), with approximate time range given for the APWP. The poles from Van der Voo [28] are estimates for the time periods 233–245, 246–266, 267–281, and 282–308 Ma. Those for Irving and Irving [30] and Torsvik et al. [31] are from 220, 240, 260, 280, and 300 Ma.

nations, even after correction for the tilt of the Phanerozoic strata.

We assert that it is possible to compare our observed paleomagnetic poles with those for the late Paleozoic of stable North America (Fig. 11) to approximate the ages of the secondary magnetizations in these rocks. One potential flaw in this argument, based on the recognition that the entire region sampled cannot be considered, strictly speaking, as part of the undeformed Mesozoic/Cenozoic craton of North America, is that we have inadequately corrected for post late Paleozoic deformation, if any, of the rocks sampled and thus biasing our poles by an inadequate correction. Appreciable vertical axis rotation affecting the sampling localities, although possible, is unlikely. Wawrzyniec et al. [35] have documented variable yet consistently clockwise rotations of crustal blocks locally along the eastern and northeastern margin of the Colorado Plateau, to latitudes of central Colorado. With the exception of Tijeras Canyon, all of our sampling localities are considerably east of the eastern margin of the plateau. For some localities, we can readily account for obvious tilting by correction for the attitudes of nearby (within a few kilometers or less) overlying strata. Such corrections are not possible at the Pikes Peak locality, however, yet given that this locality lies in the core of the Front Range of Colorado and that existing paleomagnetic data from the batholith [27] are similar to paleomagnetic poles derived from rocks of comparable age (e.g. descending part of the Keweenawan Loop), we contend that large magnitude, local tilting of these rocks was negligible. On a local scale, there is convincing evidence of small magnitude tilting of parts of the Precambrian core of the Front Range in this area [36]. We recognize that, at face value, the data from the Pikes Peak locality suggest an earliest Triassic age of magnetization acquisition (Fig. 11). However, to restore these results to a direction that would yield a mid-Permian paleomagnetic pole (e.g. about 45°N and 123°E) would require a structural correction to account for some 50° of west-side down tilt, about a tilt axis that is some 10–15° west of north. Such a magnitude of tilting is geologically unreasonable. Furthermore, although we recognize the possibility of an unrecognized plunge component to any deformation that has affected rocks at any of these localities, the magnitude of plunge, if it exists, is likely to be very small (i.e. no more than a few degrees). None of our sampling localities are close to terminations of the major basement-cored uplifts that characterize this part of the foreland. Thus, given our resulting pole positions (Fig. 11) and considering the uniform, reverse polarity of the secondary magnetizations, we suggest that the magnetizations from the Laramie Range, Sherman Granite, and Pikes Peak localities were acquired in mid-Permian time, prior to the end of the PCRS in the latest Permian. Notably, the mean pole derived from the secondary magnetization in the Sherman Granite is virtually identical to that from the Permian Ingelside Formation (latitude of 45.9°N, longitude of 122.1°E) of Diehl and Shive [37], exposed to the southeast and east of the sampling area. If this age estimate is realistic, the secondary magnetizations are considerably younger than the ages of strata immediately above the nonconformity at each locality (Kinderhookean/Osagean Leadville Limestone at the Laramie Range and Morrowan/Atokan Fountain Formation at the Sherman Granite, Morrison, and Pikes Peak localities). Consequently, we infer that the actual stabilization of the late Paleozoic remanence in the crystalline rocks did not occur during subareal exposure and weathering. Further, the presence of hematite as the primary carrier of the late Paleozoic remagnetization is not consistent with an origin by intense weathering. Rather, we suggest that remagnetization occurred during and through the waning stages of Ancestral Rocky Mountains deformation, after deposition of Pennsylvanian and Permian detritus above the regional nonconformity. Our hypothesis is consistent with the exclusively reverse polarity of the late Paleozoic remanence, implying that remanence acquisition took place after early Morrowan time [38]. This hypothesis is also consistent with considerable evidence for late Paleozoic remagnetization of Paleozoic strata in the Central and Southern Rocky Mountains, including the Cambrian Peerless Formation [39], the Cambro-Ordovician Ignacio Formation [40], the Cambro-Ordovician Bliss Sandstone [41], the lower Mississippian Leadville Limestone [6,42–44], and the middle Pennsylvanian Minturn Formation [45] as well as early Paleozoic intrusions emplaced into Proterozoic crystalline rocks in the area [46–48]. Also, the hypothesis is consistent with abundant geochemical evidence for a phase of late Paleozoic base and precious metal mineralization within central Colorado [32,49].

The presence of primary thermoremanent magnetizations in many middle Proterozoic intrusions and the tendency for the secondary, late Paleozoic magnetization to be spatially associated with the nonconformity implies that remagnetization is largely restricted to the nonconformity. In some cases (e.g. the Pikes Peak Granite), remagnetization may be associated with fluid flow along high angle fracture zones, some of which may have been active during Ancestral Rocky Mountains deformation [33,50,51]. It is permissible that secondary porosity is increased in the crystalline rocks due to unloading in Ancestral Rocky Mountains exhumation. We speculate that the penetration of basinal fluids along regional nonconformities and fracture/fault zones in Precambrian basement rocks, well away from orogenic belts, may in part reflect the pronounced increase in land elevation of North America in the late Permian with the formation of Pangea. Worsley et al. [52] estimated an average increase in elevation by over 400 m relative to the present-day configuration of dispersed continents. Permian paleoclimate models generally assume a 400–500 m increase in overall land elevation relative to today (P. Fawcett, personal communication, 1996). Supercontinent-wide uplift would have led to substantial lowering of relative ground water levels [53] and rapid draining of basins that were previously characterized by abundant evaporites earlier in the Permian.

Notably, all of the localities from which we report late Paleozoic secondary magnetizations in Precambrian crystalline rocks were subsequently affected by latest Cretaceous to early Tertiary (Laramide) contraction. For the central and southern Rocky Mountains, this is the only phase of contractional deformation to have affected these rocks since the late Paleozoic and, although many aspects of Ancestral Rocky Mountains deformation remain poorly understood [54], the magnitude of crustal shortening associated with Laramide deformation is probably of equal if not greater magnitude than that associated with Ancestral Rocky Mountains deformation. There is considerable paleomagnetic evidence from many parts of the Cordillera demonstrating that Paleozoic and Mesozoic strata were locally [41,42,55,56] if not pervasively remagnetized [57,58] during latest Cretaceous to early Tertiary time. None of the specific localities discussed here, however, yield well-grouped, well-defined magnetizations that we can confidently interpret as secondary, late Cretaceous/early Tertiary magnetizations. A plausible explanation for the absence of secondary magnetizations of late Cretaceous/early Tertiary affinity is that the late Paleozoic remanence, dominated by hematite, would be difficult to reset, in particular by burial and heating alone. However, there are several examples from sedimentary rocks in the Rocky Mountains area and vicinity where hematite carries a well-defined and well-grouped secondary magnetization that, on the basis of its direction alone, may be of late Cretaceous to early Tertiary age ([59,60], A.B. Weil, personal communication, 2001). In addition, magnetite is present in several of the rocks we have studied, and it is capable of acquiring a secondary magnetization by many processes. We hypothesize that the absence of younger secondary magnetizations, of late Cretaceous/early Tertiary affinity, suggests that the remagnetization process affecting these rocks in the late Paleozoic was unique in time and that the resulting secondary magnetization, notably carried principally in hematite, was immune to subsequent processes linked to Laramide deformation.

5. Conclusions

Late Paleozoic magnetizations of secondary origin and principally carried by hematite are contained in several different Precambrian rocks in the Rocky Mountains exposed beneath a regional nonconformity with overlying upper Paleozoic strata that developed during the Ancestral Rocky Mountains deformation. We interpret the magnetization to be of chemical origin, acquired at less than about 200°C based on fluid inclusion and geochemical evidence [29,49], during modest burial toward the waning stages of Ancestral Rocky Mountains deformation. Although subareal exposure of large areas of crystalline crust at low latitudes during Ancestral Rocky Mountains deformation in the late Paleozoic may have enhanced the ability of these rocks to acquire a secondary, late Paleozoic remanence, this was not the only process responsible for remagnetization during this time period. Our observations are consistent with the considerable petrologic and geochemical work on lowermost Paleozoic strata and immediately underlying Precambrian rocks throughout the mid-continent of North America that has demonstrated widespread, if not pervasive, potassic alteration and diagenesis, which took place well after deposition of host strata and that may be linked to petroleum migration as well as base/precious metal mineralization [3,11,61,62].

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