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1995, pp. 201-208. https://doi.org/10.56577/FFC-46.201

in:

Geology of the Santa Fe Region, Bauer, P. W.; Kues, B. S.; Dunbar, N. W.; Karlstrom, K. E.; Harrison, B.; [eds.], New Mexico Geological Society 46 th Annual Fall Field Conference Guidebook, 338 p. https://doi.org/10.56577/FFC-46

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PROGRESS TOWARD PALEOMAGNETIC IDENTIFICATION OF CA. 1.4 GA REGIONAL METAMORPHIC PULSE IN CENTRAL NEW MEXICO

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Abstract—We interpret initial paleomagnetic results to indicate that some regionally metamorphosed Mesoproterozoic rocks of central New Mexico retain magnetizations as old as 1.4 Ga with high fidelity. Recognition of ca. 1.4 Ga ChRMs relies on comparison of our data with the relatively well defined 1.45-1.40 Ga apparent polar wander path for North America. Paleomagnetic poles for this time period differ markedly from those provided by younger rocks. Preservation of ca. 1.4 Ga ChRMs is plausible given that the same rocks yield thermochronologic data with high temperature cooling ages of around 1.45 Ga. Of over 290 total samples collected from the Sandia, Manzano, and Santa Fe ranges, about 69% carry ChRMs, 49% of these are well grouped and interpreted to be of 1.4 Ga affinity. Most samples carry younger secondary magnetizations as well. The mean pole from all accepted VGPs is Lon. =210.2°E, Lat. =19.9°S in situ and Lon.=218.7°E, Lat. =22.5°S str. corr., k=10.2, 7.2, and a_{95}=11.1°, 13.4°, N=19 sites from six localities. This ancient magnetization is carried by magnetite of relatively high coercivity and laboratory unblocking temperatures (400° to 580°C) or by hematite with unblocking temperatures > 600°C. ChRM directions show no correlation with directions of maximum anisotropy. Our interpretation of the preliminary data involves remanence acquisition in response to a ca. 1.45 –1.40 Ga regional thermotectonic event of temperatures greater than 500–550°C, followed by rapid cooling to below ~300°C.

INTRODUCTION

This study was conducted to test whether paleomagnetic data can be used to identify regional thermotectonic/ metamorphic events in Mesoproterozoic rocks of central New Mexico under appropriate circumstances. Thermoremanent magnetizations (TRMs) may record the geomagnetic field following a metamorphic event (Piper, 1981). This type of magnetization is acquired over a range of blocking temperatures as a rock cools below the Curie point of the magnetic minerals present. Our approach has been to compare the pole positions, derived from of statistically well grouped TRMs in regionally metamorphosed rocks, with the appropriate apparent polar wandering (APW) path. Historically, the age range of poles defining the APW path that the observed pole falls closest to is interpreted to be the approximate age of magnetization acquisition, in this case cooling from peak metamorphic conditions. Potential shortcomings of this approach in Precambrian rocks are numerous. The utility of the method is limited by uncertainties in structural deformation after remanence acquisition, complex magnetization overprints, and the relatively poor definition (compared to the Phanerozoic) of the Mesoproterozoic APW path for North America.

With the potential limitations to obtaining reliable paleomagnetic data from Mesoproterozoic metamorphic rocks, a question pertinent to this study is: 'Why use paleomagnetism to attempt to 'date' metamorphic events when isotopic dating methods can provide more accurate and more precise "ages"?' A principal reason is that paleomagnetic methods are less costly. Also, sample collection and analysis are less time-intensive than isotopic age dating techniques. Although this kind of paleomagnetic approach will never provide the actual age of the rocks, it is an inexpensive reconnaissance tool for gathering more spatially detailed and regionally broad-based data. The bearing of this type of data on a thermotectonic event that led to the acquisition of a characteristic magnetization signature is significant.

Our study attempts to identify a Precambrian paleomagnetic signal of ca. 1.4 Ga in the Mesoproterozoic rocks of central New Mexico. The 1.4 Ga time period is particularly amenable to study because paleomagnetic poles of this age for North America are relatively well established. Mesoproterozoic rocks in the Sandia and Manzano Mountains were studied for their proximity (less than 5 km) to ca. 1.4 Ga intrusions, so that rocks could be tested for their ability to retain a ca. 1.4 Ga magnetization that is probably related to contact metamorphism (Fig. 1). If ca. 1.4 Ga magnetizations can be recognized in these rocks, then similar paleomagnetic signatures might readily be recognized in rocks more distant from 1.4 Ga intrusions. Rocks in the Magdalena and Los Pinos Mountains and the southern Santa Fe Range (Fig. 1) were chosen for their lack of spatial association with intrusions (by greater than 10 km) of 1.4 Ga ages, and are therefore useful in determining if the ca. 1.4 Ga metamorphic event is more regional in character or simply confined to those areas adjacent to ca. 1.4 Ga plutons.

BACKGROUND

Paleomagnetism

Paleomagnetic work on Mesoproterozoic rocks in the southwestern United States has been limited in scope and detail. However, for certain times paleomagnetic poles are relatively well-defined and unique. The most recent compilation of Proterozoic paleomagnetic poles from rocks of the western United States (Harlan et al. 1994) emphasized the reliability of poles of about 1.05 Ga, 1.1 Ga, and 1.4–1.45 Ga ages. The APW path from this compilation provides a modern basis by which data from this study can be compared. This compilation includes eight 1.4 Ga poles with a reliability index of three or more, assessed using Van der Voo's (1987) seven-point criteria index. In directional space for southwestern North America, the ca. 1.45–1.35 Ga paleomagnetic signatures are characterized by northeast declination and moderate negative inclination (probably reverse polarity) and southwest/moderate positive (probably normal polarity) directions.

Geology

Mesoproterozoic rocks of central New Mexico are exposed along fault-bounded uplifts related to Cenozoic extension (Williams, 1990). Detailed mapping and structural work has been done on the Mesoproterozoic rocks in all the study areas (Myers et al., 1981; Bauer, 1982; Daniel, 1992; Kirby et al., 1995; Thompson et. al., in revision). Study areas contain metavolcanic and metasedimentary supercrustal rocks between 1760 and 1650 Ma and igneous rocks emplaced between about 1650 and 1420 Ma. Most rocks reached peak metamorphic conditions of about 500°C and 4kb (Grambling et al., 1988). Locally, in the Santa Fe Range, conditions reached granulite facies (Metcalf, 1990). In the Sandia and Manzano Mountains some fault-bounded blocks reached greenschist facies peak metamorphic conditions while other fault-bounded blocks experienced amphibolite facies metamorphism (Thompson et al., in revision). High grade metamorphic rocks are found adjacent to ca. 1450 Ma plutons (Kirby et al., 1995).

Studies of Mesoproterozoic rocks in central New Mexico have used mineral assemblages, cation-partitioning, and isotopic decay schemes covering a range of closure temperatures (Table 1) to obtain quantitative information on the time-depth-temperature histories of these rocks. Thermal events that reset isotopic systems at about 1.65 Ga, 1.45 Ga, 1.35 Ga and 1.1 Ga have been recognized in thermochronologic studies of metamorphic rocks in the Sandia and Manzano Mountains, and in the Santa

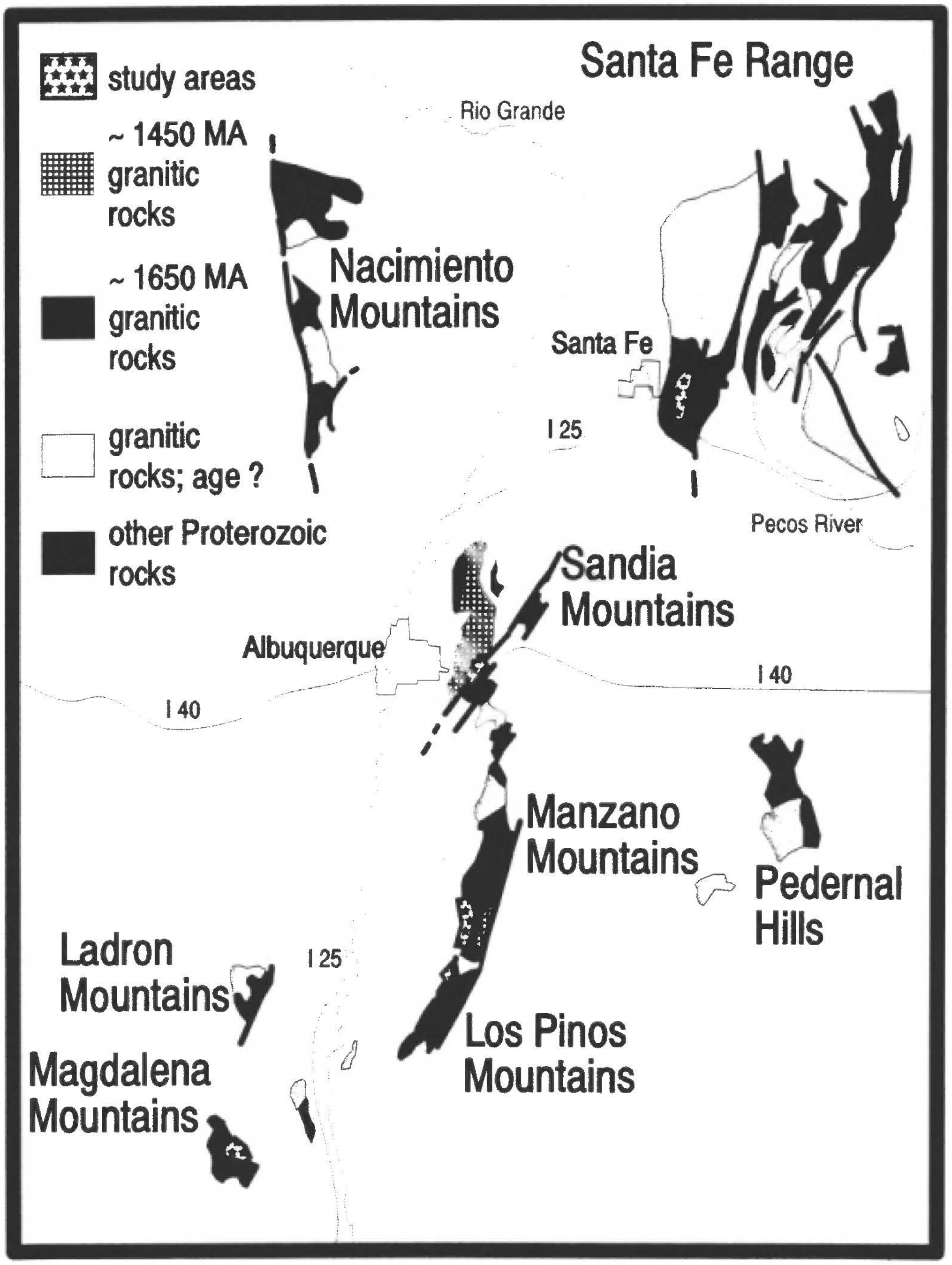

FIGURE 1. Mesoproterozoic rocks of central New Mexico with sampling localities.

Fe Range (Table 2). A substantial and growing body of data suggests that at about ca. 1450–1400 Ma Mesoproterozoic rocks in central New Mexico were at elevated (i.e. above 500°C) temperatures (Table 2). These data provide the rationale for our search for ca. 1.4 Ga magnetizations and a useful base for interpreting well-grouped paleomagnetic results characteristic of particular rock types.

The detailed studies of Mesoproterozoic rocks in each area have not dealt with paleohorizontal during the time pertinent to acquisition of magnetizations. Therefore, interpreted paleohorizontal is based on the orientation of the closest overlying Paleozoic strata. We recognize the potential shortcomings of this approach, but emphasize that our sampling in Mesoproterozoic rocks was restricted to areas well removed from localities exhibiting substantial tilt of nearby Phanerozoic strata (i.e., related to Phanerozoic deformation).

Methods

Paleomagnetic samples were collected at 30 sites (7 to 13 samples each) in the Manzano and Sandia Mountains, and in the Santa Fe Range. Rock types include amphibolites, granitic gneiss, and schist. Samples were collected as cores drilled using portable equipment. Sites were collected over an area of about 2–5 m^2 to average local magnetic effects, disturbances to outcrops, and possibly short term field variations. Specimens were prepared as either 11 cm^3, 2.2 cm^3, or 1.2 cm^3 right cylinders.

The Natural Remanent Magnetization (NRM) was measured using a 2G Enterprises Model 760R cryogenic magnetometer and specimens from independently oriented samples were then progressively demagnetized using thermal or alternating field (AF) methods. Well-defined and directionally well-grouped magnetizations removed at consistent and relatively high alternating fields or unblocking temperatures were con-

TABLE 1. Blocking temperatures for five isotopic systems and two ferromagnetic minerals for comparison. Paleomagnetic blocking temperatures depend upon grain size and shape as well as mineral composition. Magnetic blocking temperatures are roughly represented by laboratory unblocking temperatures (Dunlop, 1981).

Method	Mineral	Blocking Temperature	References
$^{40}Ar/^{39}Ar$	hornblende	525 +/- 25°C	Harrison and FitzGerald, 1986;Harrison et al., 1985;
	biotite	280° to 350°C	Robbins, 1972; Dodson, 1973; Berger and York, 1981
	muscovite	~350°C	
U/Pb	zircon	800+ °C	Mezger et. al., 1991; Heaman and Parrish, 1991; Mattinson, 1982
	sphene	500° to 600°C	
	apatite	400°C	
Rb/Sr	biotite	250°C	Hart, 1964; Van Breeman and Dallmeyer, 1984
Fission Track	sphene	290° +/- 40°C	Kelly and Duncan, 1986; Poupeau, 1969
	apatite	75° to 125°C	
Paleomagnetism*	magnetite	200° to 580° C	Tarling, 1983; Butler, 1992
	hematite	580° to 680° C+	

sidered characteristic of the rocks (ChRMs). Site means with directions that could be associated readily with younger or older age magnetizations or that were greater than two standard deviations from the mean were not used to determine grand means. Anisotropy of magnetic susceptibility (AMS) was measured using a Sapphire SI-2 induction-coil instrument to assess whether magnetizations were influenced by rock textures/magnetic fabrics. A more detailed discussion of methods used in this study can be found in Meuret (1995).

RESULTS

Contact rocks

Of four localities sampled (three from the Manzano Mountains and one from Tijeras Canyon with several sites each), at least one site from each yielded a well-grouped ChRM interpreted to be of ca. 1.4 Ga age. Of 214 samples demagnetized, about 90% yielded interpretable results. About 66% of the interpretable sample results were used to determine means; 7% of the directions omitted were more than two standard deviations from estimated mean directions. The other 27% of interpretable, yet omitted results were judged to carry only secondary magnetizations. About 61% of the samples used to determine site means resulted in 12 well-grouped site means (Fig. 2a).

In general, ChRMs were either not removed using AF techniques or removed only over a range of very high fields (i.e., 50 mT–90 mT). Thermally demagnetized samples from all but three of the well-grouped sites lost their ChRMs over a narrow range of blocking temperatures (about 540°C to 590°C), typical of single- or pseudo-single-domain magnetite as the dominant magnetic phase (Figs. 2b–2c). Petrographic inspection demonstrated the presence of needle-shaped magnetite in rocks from most of these sites. The remaining three sites (all from felsic rocks) yielded ChRMs at temperatures > 600°C (typical of hematite, the presence of which was verified by petrographic inspection).

Regionally metamorphosed rocks remote from intrusions

Of four localities sampled (two from the Santa Fe Range, one in the Los Pinos Mountains and one in the Magdelena Mountains), only the two in the Santa Fe Range contained at least one site with well grouped ChRMs. The other two localities are not further considered here. Of 76 samples demagnetized from the southern Santa Fe Range, about 96% were interpretable. About 77% of the interpretable remanence directions were used to determine site means. The remaining 23% of directions identified were more than two standard deviations from the mean. Seven site means were determined and four of these were statistically acceptable (Fig. 2d).

In general, ChRMs were either partially removed using AF techniques or fully removed at relatively low fields (i.e. 12 mT–40 mT; Fig. 2g). Most thermally demagnetized samples lost their ChRMs over a range of blocking temperatures (about 300° to 570°C; Fig. 2f). At one site ChRMs were consistently unblocked over a narrow range of temperatures (about 540°C to 590°C), typical of single or pseudo-single domain magnetite (Fig. 2e). Petrographic inspection of this site revealed the presence of small (less than 15 μm, euhedral magnetite grains. Petrographic inspection of two other sites revealed the presence of medium (20–100 μm, euhedral magnetite grains.

Anisotropy of magnetic susceptibility

Most rocks used in this study are characterized by a strong degree of magnetic anisotropy. For amphibolites, it is estimated that paramagnetic minerals dominate the AMS signature (Borradaile et al., 1987). For intermediate and granitic rock types it is estimated that the magnetic fraction dominates the AMS fabric (Borradaile et al., 1987). It appears that, for most sites, the primary directions of the AMS reflect the penetrative silicate fabric in the rocks. Results show little or no correlation among directions of well-defined, accepted site means, directions of principal susceptibility axes, and/or dispersion of maximum magnetic susceptibility.

TABLE 2. Isotopic data from sampled localities.

Mountain Range	$^{40}Ar/^{39}Ar$ hbl	$^{40}Ar/^{39}Ar$ bt	$^{40}Ar/^{39}Ar$ ms	U/Pb zr	U/Pb sph	U/Pb ap	Rb/Sr wr	Fission Track sph	Fission Track apt	References
Sandia	1400-425	1350	1423-1000	1437			1576-1407	1400-545	50-25	Steiger & Wasserburg, 1966; Poupeau, 1969; Kelly and Duncan, 1986; Kirby et al., 1995 Thompson et al. in revision; Karlstrom & Dellmeyer, in prep
Manzano	1437-1427		1360-1100	1427						Heizler and Ralser, 1994; Thompson et al. in revision; Karlstrom & Dallmeyer, in prep
Santa Fe	1427, 1430		1274	1650, 1720			1465			Bowring & Condie, 1982; Karlstrom & Dallmeyer, in prep

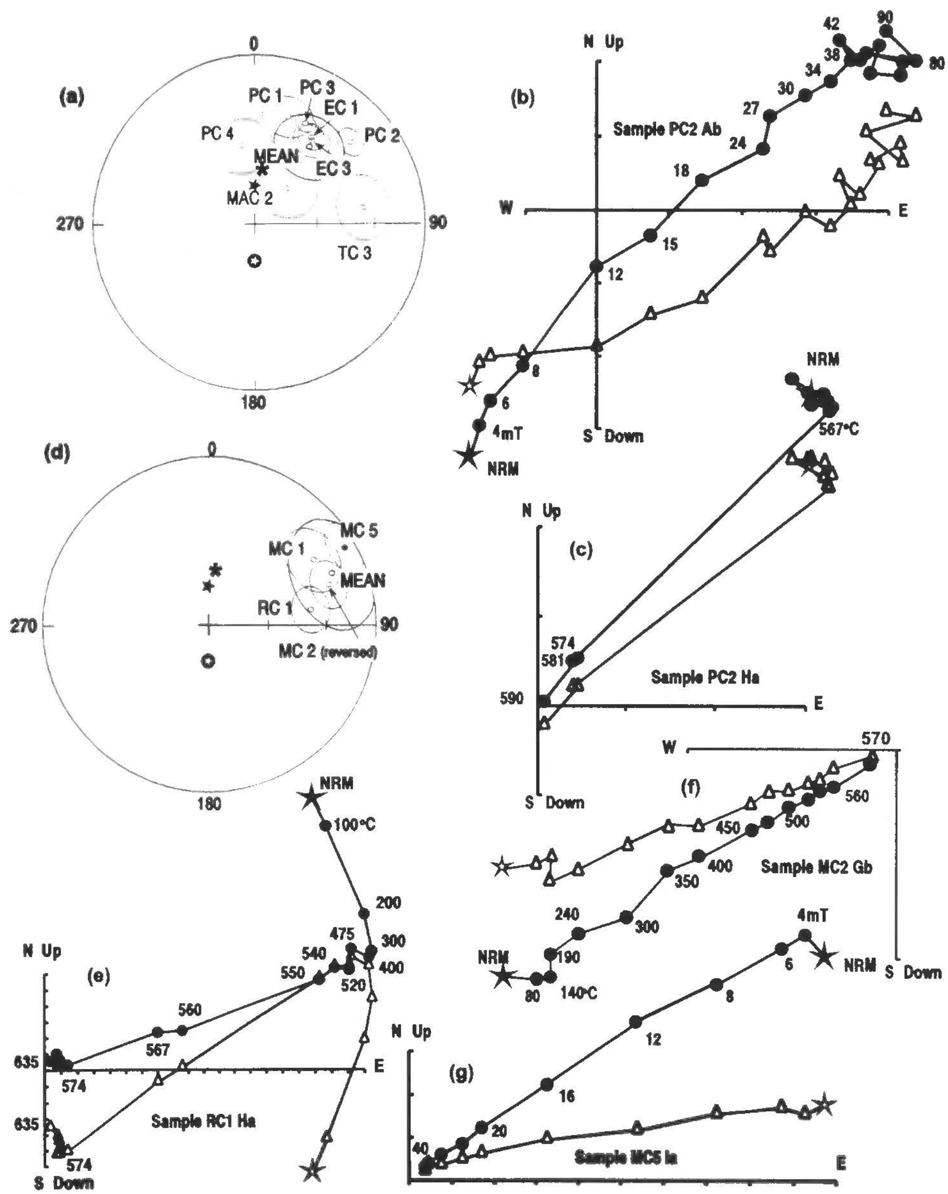

FIGURE 2. a, d, Equal area projections of site means with α95s <15o and their associated cone of 95% confidence from rocks near 1.4 Ga granites (a), and far from 1.4 Ga granites (d). Open symbols represent negative inclinations, closed symbols represent positive inclinations. The asterisks represent the present field and the stars represent the Axial Geocentric Dipole. b, c, e-g, Orthogonal projections of demagnetization results. Scaling is as follows: 1 division = 1x10-4 A/m (b); 1 division = 1x10-3 A/m (c, g); 1 division =1x10-2 A/m (e); 1 division = 1 A/m (f).

DISCUSSION

Metamorphic rocks, having populations of magnetic phases with appropriate grain size and shape combinations in central New Mexico, yield well-grouped ChRMs that we interpret to be Mesoproterozoic (ca. 1.40 Ga) in age. Complicating this interpretation are numerous samples with uninterpretable demagnetization behaviors and poorly grouped results, high percentage AMS fabrics, and uncertainties regarding the paleohorizontal. Despite these difficulties, which we believe to be inherent to deciphering Precambrian magnetizations in tectonometamorphic terrains, we argue that the well-grouped ChRMs are Mesoproterozoic. This interpretation is based mainly on the anomalous directions of the ChRMs, their demagnetization characteristics, and available $^{40}Ar/^{39}Ar$ data. Directions of magnetizations isolated at localities near ca. 1.4 Ga granites are significantly different from the four sites at localities distant from ca. 1.4 Ga granites (Fig. 3). This difference may reflect analytical and/or tilt correction errors or a difference in age of magnetization blocking.

Compared to many studies of Phanerozoic igneous rocks, we accepted much lower k values and much higher α95 values for individual sites. The average k value of the sites accepted is 34 and the mode is 23 with three values less then 10. The average α95 value is 15° and the mode is 13°. For comparison, we inspected average k and α95 values from three other studies in Precambrian rocks. Of the six localities reported by Schutts and Dunlop (1981) the average k is 29 and the average α95 is 8.3°. Of 61 sites reported by Piper (1981) the average k is 267 and the mode is 143. Of 41 sites reported by Harlan et al. (1994) the average k is 87 with a mode of 48; the average α95 is 9.5°. Values obtained in the present study are slightly more scattered than those discussed above. However, most studies of Precambrian rocks (including the examples used above) are from igneous rocks and their immediate baked contacts, not highly deformed medium- to high-grade metamorphics. A larger amount of directional scatter should be expected for such materials and a smaller probability of success anticipated.

Many rocks used in this study were well foliated and thus had a high percentage AMS. Results of a site level analysis show that ChRM directions, in general, were not controlled by the AMS. However, this does not preclude influence at the sample level. Relatively large α95s (compared to

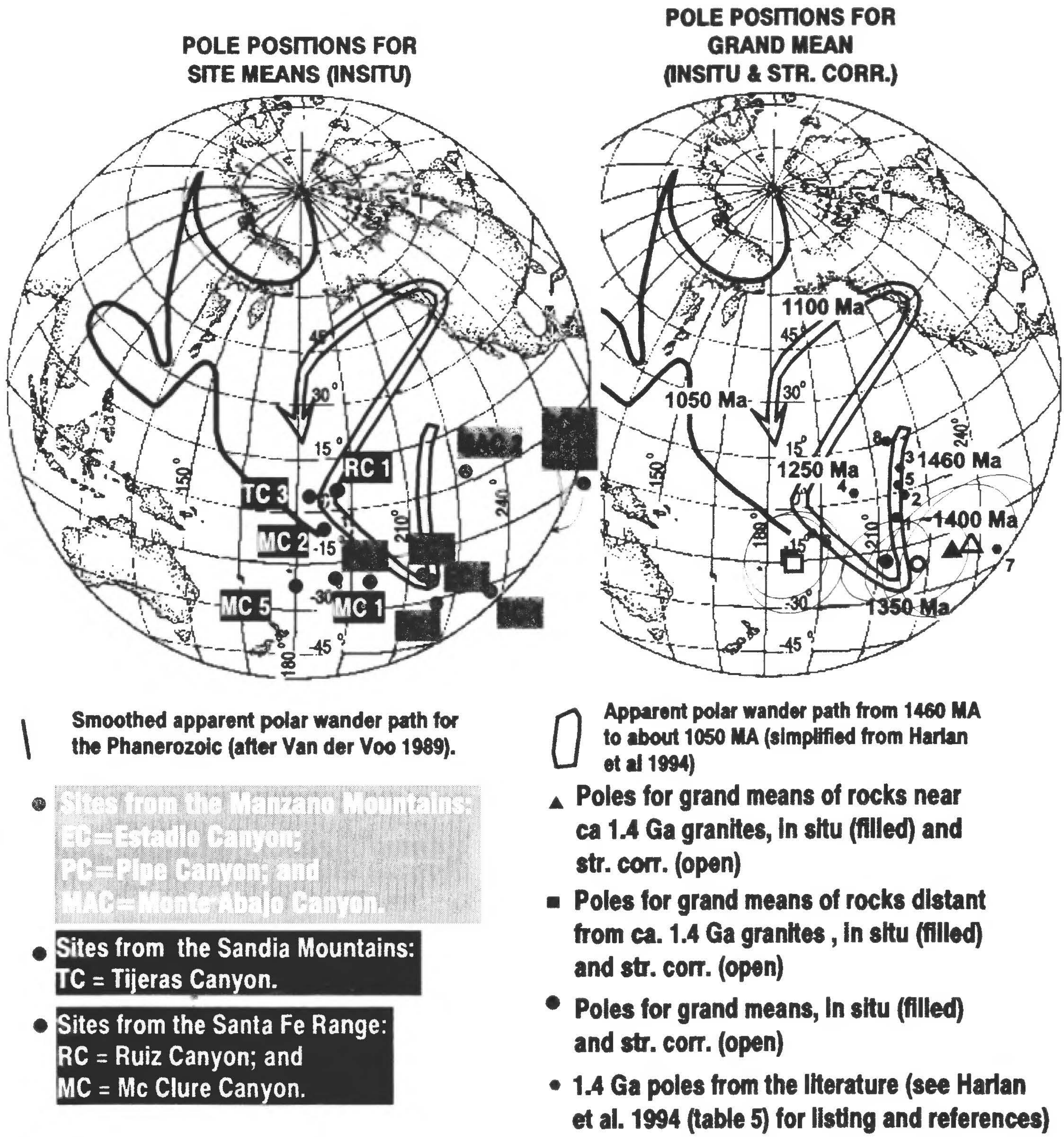

FIGURE 3. Virtual geomagnetic pole positions for site means and grand means. For the grand mean of rocks near ca. 1.4 Ga granites α95=17.5o; k=9.6 in situ and 19.0o; k= 8.3 str. corr.. For the grand mean of rocks distant from ca. 1.4 Ga granites the mean α95=13.1o; k=50.1 in situ and 17.1o; k=29.7 str. corr.. For the grand mean of all rocks the mean α95=11.1o; k=10.2 in situ and 13.4o; k=7.2 str. corr.. The small numbers mark the poles from the following locations: 1, Laramie anorthosite, WY; 2, Michikamau anorthosite, Labrador; 3, Croker Island Complex; 4, Harp Lake anorthosite; 5, St. Francois volcanics; 6, Front Range, CO & WY; 7, Medicine Bow Mt., WY; and 8, Tobacco Root Mts., MT(?); see Harlan et al. (1994, Table 5) for references.

most unfoliated rock types) might reflect influence by penetrative fabrics.

Because paleohorizontal during the time of magnetization acquisition is impossible to determine, interpreted paleohorizontal was based on the orientation of the closest overlying Paleozoic (Mississippian or younger) strata. This approach is limited because it does not take into account possible pre- Late Mississippian deformation. Displacement by numerous Phanerozoic faults may contribute to the scatter between sites. In a regional sense, ca. 1650–1450 Ma rocks exhibit subhorizontal isotherms and isobars, suggesting that Mesoproterozoic rocks have not been substantially disturbed (Grambling, 1986).

Despite these caveats, there is convincing evidence that ChRMs from rocks adjacent to and more distant from ca. 1.4 Ga granites are ca. 1.4 Ga in age. Directions of remanence for 18 out of 22 ChRM site means differ from the present field by more than 80° (Table 3; Fig. 2). The mean paleomagnetic pole derived from 19 site virtual geomagnetic poles (VGPs; Fig. 3) is distinct from Phanerozoic poles for North America. Some sites yield very well-grouped ChRMs (EC 1, EC 3, PC 2 and PC 3). These site VGPs cluster closely around the grand mean (Fig. 3), which is similar to ca. 1.4 Ga paleomagnetic poles.

Sites MC 3 and MC 4 pass the reversal test with respect to other sites from that locality. Most other sites contained one or more samples considered antipodal to the site means. Although these data are not as reliable as a reversal test based on numerous site means, the implications are the same. A positive reversal test is highly unlikely with dispersed directions of magnetization; antipodal directions of remanence within sites are consistent with slow cooling relative to the time required for reversal of the geomagnetic field. Short-term secular variations of the field are well averaged at the site level.

At all sites (except TC 3, EC 2 and EC 3) ChRMs are carried by magnetite that is typically not a product of low temperature chemical alteration. Petrographic observations revealed fine, needle-shaped, and small square magnetite or titanomagnetite occurring as inclusions in amphibole or plagioclase in representative samples from most sites. Magnetizations are interpreted to be carried by these grains. Magnetizations in rocks with needle-shaped grains had high coercivities and could not be removed using AF methods. In thermal demagnetization, 80 to 90% of the total remanence was unblocked between 400°C and 590°C. This range of unblocking temperatures is consistent with the rocks cooling to below around 300°C soon after acquisition at 1.3–1.4 Ga and the absence of a significant reheating event. Furthermore, most magnetite grains are observed as inclusions in Fe/Mg silicates or plagioclase and may be relatively protected from chemical remagnetization. These grains may be of high temperature, metamorphic origin.

At many sites a well-grouped secondary magnetization of low unblocking temperatures and coercivities is removed before the ChRM is isolated. The north-directed, positive inclination of most secondary remanences is consistent with a young (e.g., Cretaceous or younger) age. These magnetizations may record Laramide or younger uplift. The ChRMs must be older than this partial remagnetization and were resistant to the process that led to partial resetting.

TABLE 3. Site mean and summary statistics for magnetizations of high unblocking temperatures and coercivities.

Site	$n (n_t)/N(N_t)/N_o$	dec	inc	ê (k)	á95(A_{95})	rsum
	Contact Rocks					
TC 1	9(8)/7(7)/9	124.3	-45.7	48	8.8	6.875
TC 3*	11(10)/6(6)11	81.4	-35.3	23.3	14.2	5.785
TC 4	12(11)/6(5)/11	321.8	59.9	25.6	13.5	5.804
TC 9	20(10)/11(3)/20	76.9	-31.6	3.8	26.9	8.401
TC 11	10(2)/5(1)/10	110.8	-28.4	18.6	18.2	4.785
EC1*	9(7)/6(3)/7	33.2	-38.4	118.8	6.2	5.958
EC2*	4(4)/4(4)/4	2.4	-60.5	24.8	18.8	3.879
EC3*	11(9)/8(2)/9	34.4	-39.7	43.1	8.5	7.837
EC4	10(9)/4(4)/9	19.9	-43.3	12.1	27.5	3.753
EC6	13(10)/8(8)/10	36.7	-39.6	5.2	26.8	6.663
EC7	12(10)/9(9)/10	330.1	-29.3	14.1	14.2	8.432
PC 1*	18(10)/6(6)/10	17.2	-33.6	38.5	10.9	5.87
PC 2*	13(10)9(9)/10	49.3	-26.3	65.2	6.4	8.877
PC 3*	15(10)/9(9)/10	26.9	-33.5	131.2	4.5	8.939
PC 4*	13(7)/5(4)/7	351	-49.1	34.6	13.2	4.884
MAC2*	10(9)/6(6)/9	42.7	-66.4	22.9	14.3	5.781
MAC4	14(12)/11(9)/12	38.6	-8.2	6.1	20.2	9.357
Grand Mean	8 sites; á95< 15°	35.2	-43.0	12.7	16.2	7.449
VGP Mean	8 sites; á95 <15°	224.3E	20.2S	9.6	17.5	8.168
	Regionally Metamorphosed Rocks Remote from Intrusions					
RC 1*	16(10)/9(9)/10	80.9	-36.5	20.8	11.6	8.615
RC 2	15(8)/6(6)/8	41.8	-37.9	9.8	22.5	5.221
MC 1*	20(8)/6(6)/8	58.3	-26.4	42.6	14.2	3.930
MC 2*	16(7)/7(5)/11	251.5	24.7	37	10.1	6.838
MC 3	16(5)/9(5)/13	250.3	-21.4	5.2	24.9	7.47
MC 4	11(4)/(4)(2)/7	240	3	13.8	25.6	3.783
MC 5*	21(7)/10(3)/14	60.4	6.9	24.1	10	9.627
Grand Mean	4 sites; á95 < 15°	67.3	-20.9	14.5	24.9	3.794
+10° 90°	4 sites; á95 < 15°	65.0	-29.0	14.5	24.9	3.794
+20° 90°	4 sites; á95 < 15°	63.0	-38.0	14.5	24.9	3.794
VGP Mean	4 sites; á95 < 15°	188.4E	12.8S	50.1	13.1	3.940
	Overall Grand Mean					
Grand Mean	19 sites; á95 < 30°	45.9	-35.6	9.4	11.5	17.093
VGP Mean	19 sites; á95< 30°	210.2E	19.9S	10.2	11.1	17.234

*	sites used to determine grand means	dec	site mean declination
n	number of specimens demagnetized	inc	site mean inclination
(n_t)	number of specimens demagnetized thermally	ê (k)	kappa (concentration parameter)
N	number of samples accepted for calculations	á95(A_{95})	cone of 95 percent confidence
N_t	number of thermally demagnetized samples accepted for calculations	rsum	vector sum of site mean
N_o	number of samples demagnetized		

Rocks near those yielding well-grouped paleomagnetic results retain $^{40}Ar/^{39}Ar$ dates from hornblende between 1437 Ma and 1400 Ma (Table 2). Most ChRMs were likely acquired at this time. Also, the hornblende age spectra suggest that the area has not been significantly reheated relative to the blocking temperature of Ar in hornblende (500°C +/- 25°C; Table 1). $^{40}Ar/^{39}Ar$ dates obtained from biotite and/or muscovite are also Mesoproterozoic in age. Values range between 1423 Ma in the Manzano Mountains and 1350 Ma in the Sandia Mountains to between 1337 Ma and 1274 Ma in the Santa Fe Range (Table 2). Retention of Ar by muscovite and biotite suggests that the area has not been significantly reheated relative to the blocking temperatures of Ar in these minerals (around 350°C for fast cooling or around 280°C for slow cooling; Table 1) since the late Mesoproterozoic.

Of particular interest are the differences in observed directions between sites from localities adjacent to and distant from ca. 1.4 Ga granite (Fig. 2; Table 3). Twelve site means (11 from the Manzano Mountains and one from the Sandia Mountains) with $\alpha95$s less than 15° were isolated from rocks near ca. 1.4 Ga granites. Out of seven sites distant from ca. 1.4 Ga granites, only four well-grouped site means were isolated (from two Santa Fe Range localities). The mean VGPs from the Santa Fe Range are distinct from those isolated in the Manzano and Sandia Mountains at the 95% confidence level (Fig. 3). These differences in directions can be explained in many ways, and we discuss two possibilities. The first is that ChRMs from the different areas are of different ages. The grand mean for sites from the Manzano and Sandia Mountains plots near the ca. 1.4 Ga part of the APW path. The grand mean for sites from the Santa Fe Range plots near the ca. 1.3 Ga part of the APW path. Differences in demagnetization characteristics, as discussed above, and $^{40}Ar/^{39}Ar$ age spectrum data are consistent with this interpretation.

In the context of thermomagnetization behavior, lower unblocking temperature and coercivity grains are more easily reset by thermal activation and/or remain unblocked at moderate temperatures (Dunlop, 1981). As an example, if temperatures remained above 375° for 10 Ma the fraction of these carriers unblocked below 490°C would be reset (e.g., Dunlop, 1981). ChRMs unblocked between 550°C and 590°C would not be activated as long as temperatures remained below about 510°C.

In the Manzano Mountains and the Santa Fe Range $^{40}Ar/^{39}Ar$ plateau dates from hornblende are similar. They range between 1437 Ma and 1400 Ma in the Manzano Mountains and 1430 Ma and 1420 Ma in the Santa Fe Range (Table 2). $^{40}Ar/^{39}Ar$ dates obtained from muscovite in the Santa Fe Range are slightly younger than those from the Sandia and Manzano Mountains. Ages range from 1274 Ma to 1337 Ma in the Santa Fe Range and from 1350 Ma to 1423 Ma in the Sandia and Manzano Mountains (Table 2). Overall these dates suggest that cooling was slower in the Santa Fe Range.

Not all of our results are consistent with this explanation. ChRMs from site TC 3, close to the Sandia granite, are similar to data from the Santa Fe Range. This site is from a major fault zone and the ChRMs are carried by hematite, which could have originated during fluid flow along the Tijeras Canyon fault zone well after 1.4 Ga. The data from sites TC 1and TC 11 suggest that partial remagnetization probably occurred during the late Paleozoic (Fig. 2). Site RC 1 is more problematic because the high unblocking temperatures of rocks at this site suggest that they should retain ChRMs from the time of cooling below 580°C through about 500°C. Although $^{40}Ar/^{39}Ar$ dates from hornblende imply that this should be between 1420 and 1430 Ma, ChRM directions are similar to those sites with lower unblocking temperatures.

The second explanation involves unrecognized tilting to produce differences in ChRM directions. The Santa Fe Range, where all the well-grouped sites distant from ca. 1.4 Ga granites form, is the only area sampled where there are no overlying Paleozoic rocks on which to base tilt corrections. All Paleozoic rocks are in fault contact with Mesoproterozoic rocks. Preliminary tilt correction was based on the regional tilt of Paleozoic rocks. Tilt correcting these sites based on the style of deformation expected for the eastern edge of the Rio Grande Rift brings them very close to ChRM directions from ca. 1.4 Ga contact aureoles (Table 3). Despite the unavoidable complexity of appropriate tilt corrections, retention of ca. 1.4–1.3 Ga ChRMs at these localities suggests that heating at ca. 1.4–1.3 Ga was not limited to contact aureoles. The conflict that site RC 1 presents with respect to the first explanation does not exist in this explanation, because site RC 1 is restored to general agreement with 1.4 Ga results as well as the MC sites. This mechanism requires that the lower unblocking temperature magnetite fractions of the MC sites did not record the younger cooling, as suggested by $^{40}Ar/^{39}Ar$ dates from muscovites.

The data obtained to date are insufficient in overall quality to clearly distinguish between possible explanations offered. Single sites (e.g., RC 1) cannot be relied upon to accurately reflect magnetic blocking histories for an entire area. More well-grouped site data are required to facilitate interpretation of the differences between ChRM directions from rocks adjacent to and distant from 1.4 Ga intrusions without ambiguity. With such data, the relationship between observed ChRMs and the ca. 1.4 Ga remagnetization event can be better understood.

IMPLICATIONS AND SUMMARY

In the past, because most ca. 1.4 Ga intrusions in the southwestern United States lacked obvious tectonic fabrics, a common assumption was that these intrusions were anorogenic (Anderson, 1983). More recently, recognition of tectonic fabrics within and at the margin of ca. 1.4 Ga intrusions (Nyman et al., 1994, Kirby et al., 1995) and isotopic age data indicating elevated temperatures distant from ca. 1.4 Ga intrusions (Karlstrom and Dallmeyer, and Lanzirotti, personal commun., 1995) have led workers to revise interpretations. An emerging consensus is that ca. 1.4 Ga intrusions are associated with a widespread regional thermotectonic event.

Rock magnetic tests, demagnetization characteristics and petrographic observations indicate that rocks are capable of retaining Mesoproterozoic age (ca. 1.4 Ga) paleomagnetic signatures. Accepted site means from ca. 1.4 Ga aureoles yield ChRMs with VGPs similar to previously obtained ca. 1.4 Ga poles (Fig. 3). Structural correction slightly increases dispersion as well as the disagreement of our VGPs with the APW path. VGP locations based on the sites from the southern Santa Fe Range differ significantly from those from localities close to ca. 1.4 Ga granites (Fig. 3). Two possible explanations — that magnetizations from the Santa Fe Range are of younger ages or that differences in direction are the result of unrecognized Phanerozoic tilting are reasonable. If the former is true then no clear conclusions can be drawn about the nature of the ca. 1.4 Ga metamorphic pulse. If likely Cenozoic tilting is corrected for, then all magnetizations appear to be ca. 1.4 Ga old (Table 3). It would then be likely that localities distant from ca. 1.4 Ga intrusions also yield VGPs similar to ca. 1.4 Ga poles. Regardless of this complexity, overall, the paleomagnetic data are interpreted to suggest that the ca. 1.4 Ga metamorphic event is perhaps more regional in character than previously assumed. Further paleomagnetic analysis will be useful for an improved understanding of the thermal history of Mesoproterozoic rocks in central and northern New Mexico.

ACKNOWLEDGMENTS

This study was funded by a fellowship from the U.S. Geological Survey under the supervision of Dr. Clay Conway and by grants from the UNM Earth and Planetary Sciences Department scholarship fund. We would like to thank Bill McIntosh and Rick Liviccari for their critical reviews.

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