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REMAGNETIZATION ALONG THE PERMIAN-TRIASSIC DISCONFORMITY IN CENTRAL NEW MEXICO AND REMANENCE ACQUISITION IN THE MOENKOPI FORMATION

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Abstract—Sites collected from carbonate rocks and red beds near and at the disconformity between Permian and Triassic strata of the San Andres and Moenkopi formations, respectively, in central New Mexico, contain secondary magnetizations carried by goethite (G) and hematite (H). Paleomagnetic field tests show that normal polarity, north directed and steep magnetizations (Gn and Hn) are likely to be of recent origin, but that reverse polarity, south directed and steep magnetizations (Gr and Hr) are ancient magnetizations. In Triassic strata, Hr magnetizations are superimposed on an early acquired ("primary") magnetization. The primary magnetization of the Moenkopi Formation was locked-in during or soon after deposition, but acquisition of a shallow, low unblocking temperature, magnetization continued long after that. In carbonate rocks of the San Andres Formation, remagnetization is more pervasive, and Hr magnetizations have been identified in facies containing hematite/goethite replacements of evaporite nodules and goethite pseudomorphs of pyrite crystals. Magnetizations with similar directions are observed near the unconformity over a broad region of central and western New Mexico, suggesting that a regional tectonic or diagenetic event may be associated with acquisition of these magnetizations. Hr magnetizations cluster significantly better after correcting for structural tilt related to Rio Grande rift extension. Gr magnetizations are better grouped before tilt correction and give a paleopole indistinguishable from the Late Tertiary–Quaternary dipole field. Clasts of carbonate rocks and hematitic sandstones in the Eocene Baca Formation, lying disconformably above Triassic strata, carry random magnetizations and place a minimum limit on the time of acquisition of the Hr magnetizations. The mean pole calculated for 12 sites from four localities (Lat. = 71.4°, Long. = 157.9°E; A95 = 5.1°) is indistinguishable from poles derived from the Upper Jurassic Morrison Formation from the Colorado Plateau and northeastern New Mexico.

INTRODUCTION

The characteristic magnetization of red beds is generally a chemical remanent magnetization (CRM) that resides in hematite (Walker et al., 1981). CRM in red beds is considered to be acquired after sediment deposition, but on time scales more rapid than that of apparent polar wander (Butler, 1992). This inference is based on the fact that red beds yield paleomagnetic poles that are generally consistent with poles derived from coeval volcanic rocks and on the observation of bedding parallel magnetic polarity zonations (e.g., Kent et al., 1995). Field tests are, however, the only means to establish unequivocally the relative timing of remanence acquisition of the CRM, and this shall always be of concern in studies of such rocks (Purucker et al., 1980; Larson et al., 1982).

The "secondary" nature of fine-grained microcrystalline and polycrystalline hematite grains in red beds is well established (Walker et al., 1981). It is also generally accepted that the remanence in red beds is the sum of the contributions from fine-grained hematite, which is normally characterized by magnetizations of low and distributed ublocking temperatures, and coarse-grained "specular" hematite, which normally exhibits higher unblocking temperatures (Collinson, 1974). Ultrafine pigmentary hematite is superparamagnetic and does not contribute to the remanent magnetization. Researchers typically consider high unblocking temperature magnetizations to be more reliable recorders of the geomagnetic field, but it has also been shown that specular hematite grains are not necessarily detrital in origin and that specular hematite can be produced by in situ alteration after depostion (Van Houten, 1968), supporting the chemical origin of the magnetization of red beds. Less attention has been paid to the general observation that magnetizations of low distributed unblocking temperature may be both ancient and recent in origin.

Carbonate rocks, on the other hand, retain weak depositional or post-depositional remanent magnetizations (PDRM) acquired soon after deposition, that may reside in magnetite, hematite, or magnetic sulfides. Paleomagnetic data for red beds are often considered more reliable than those for carbonate rocks, because remanence carriers in carbonate rocks are more susceptible to diagenesis, leading to partial to complete obliteration of the primary remanence. Nevertheless, acquisition of secondary magnetizations in hematite and magnetite-bearing sedimentary rocks is now recognized as a widespread phenomenon (McCabe and Ellmore, 1989).

Here, we present field evidence showing that the remanent magnetization of red beds of the Moenkopi Formation in central New Mexico is the sum of two ancient magnetizations. One is a high unblocking temperature magnetization that was acquired during or soon after deposition. The other is a lower and distributed unblocking temperature magnetization, a CRM acquired after deposition. We also show that, associated with the Permian-Triassic disconformity in central New Mexico, a regional remagnetization event led to acquisition of secondary CRMs that reside in hematite and goethite in both red beds and carbonate rocks. We hypothesize that the Permian-Triassic disconformity acted as a preferred pathway for migrating fluids causing acquisition of secondary magnetizations. Determining the timing of remanence acquisition with respect to episodes of uplift and erosion, and a full characterization of the magnetization carriers, may provide additional clues for understanding remagnetization processes.

GEOLOGY, SAMPLING, AND METHODS

Across New Mexico, Middle Triassic red beds of the Moenkopi Formation disconformably overlie Upper Permian rocks of the Artesia Group, mostly evaporites and continental red beds, or the San Andres Formation, a marine transgressive sequence of latest Early Permian age (Kottlowski, 1968). Our sampling centered on the Permian-Triassic disconformity in the Joyita Hills, a horst in the southern part of the Albuquerque-Belen basin of the Rio Grande rift (Fig. 1). Sites mo41–mo49 were collected from gently west-dipping Moenkopi strata directly overlying the Permian-Triassic disconformity. The lowermost site in Moenkopi strata (mo41) is 0.75 m above the unconformity surface, overlying a thin package of friable mudstone. The overlying section, where the other sites were collected, is approximately 25 m in thickness. The Moenkopi Formation is one of the paleomagnetically best characterized rock units of southwestern North America; samples for this study were collected primarily to establish the timing of acquisition of primary and secondary magnetizations previously observed in Moenkopi strata (Molina Garza et al., 1991). The underlying San Andres Fromation was sampled at six sites in the Joyita Hills (sa1–sa4, sa40, sa53) and at sites in the Lucero (sa-luc) and Los Pinos uplifts (sa–lp). San Andres limestones locally contain high densities of hematitic veinlets, typically less than 1 mm in thickness. Site sa3 consists of fine-grained hematitic cave deposits, with sites sa2 and sa4 in surrounding limestone. At sites sa40 and sa53, we sampled rocks with

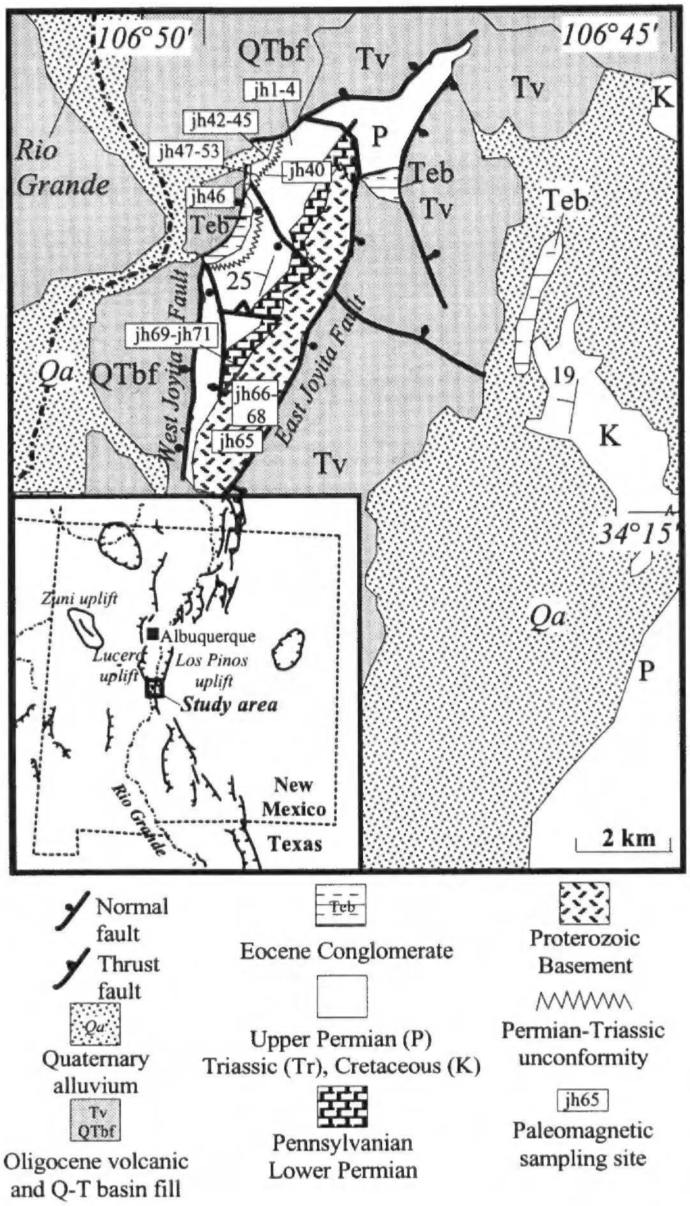

FIGURE 1. Simplified geologic map of the Joyita Hills (after Wilpolt et al., 1946) indicating sampling locations. The inset shows a simplified tectonic map of New Mexico with localities discussed in the text.

abundant mm-size hematite/goethite intergrowths interpreted to replace gypsum layers and nodules. In addition to this, five sites were collected in uplifted Precambrian basement rocks (jh65–69) and overlying upper Paleozoic strata (mf70 and bf71) in the south-central Joyita Hills with detailed sampling of the Precambrian-Paleozoic nonconformity. Samples were collected with a portable drill using a non-magnetic drill bit and oriented with magnetic/sun compass and clinometer.

For a conglomerate test, we sampled clasts of red sandstone and carbonate rocks in the Baca Formation, a boulder conglomerate that postdates local Laramide-style deformation in the Joyita Hills (sites ba46, ba50). For a more detailed conglomerate test, intra-formational, millimeter size, rip-up clasts and mudstone-chips in the Moenkopi Formation from one of the sites were prepared for NRM measurements. All specimens were subjected to progressive thermal or alternating field (AF) demagnetization up to temperatures of 695°C or inductions of 130 mT. The vectorial composition of the NRM was determined by inspection of orthogonal demagnetization diagrams (Zijderveld, 1967). Directions of the magnetization components were determined using principal component analysis (Kirschvink, 1980). Paleomagnetic data are summarized in Tables 1 and 2.

PALEOMAGNETIC RESULTS

The NRM of the San Andres limestones is normally multivectorial and of moderate to low intensities, typically less than 5×10^{-4} A/m. In most cases, AF demagnetization fails to remove a significant remanence; only a small, north-directed magnetization component of steep positive inclination is identified. Thermal demagnetization reveals the presence of low unblocking temperature magnetizations, with either south-directed and steep negative inclination (Gr magnetizations; Fig. 2a, b), north-directed and steep positive inclinations (Gn), or both (Fig. 2c). Gn magnetizations have maximum unblocking temperatures of about 300°C, but typically a small Gn magnetization is removed by heating to 80°C and again between 125° and 300°C. Gr magnetizations have maximum unblocking temperatures of 125°C.

Higher unblocking temperature magnetizations have distributed unblocking temperature spectra with either north-directed, moderate-to-steep, positive inclinations (Hn, Fig. 2a) or south-directed magnetizations of moderate-to-steep negative inclination (Hr, Fig. 2b). Maximum unblocking temperatures of H magnetizations are about 650°C. At two sites, sa2 and sa4, the characteristic magnetization (ChRM) is of (in situ) moderate inclination and intermediate unblocking temperature and coercivity. It unblocks between 350 and 500°C (Fig. 2c) and thus possibly resides in magnetite.

Initial NRM directions of Moenkopi sandstones are either southeast-directed and shallow or north-directed and of moderate to high positive inclination. The NRM is of moderately high intensity (>1×10^{-3} A/m) and high coercivity. Response to AF demagnetization is either insignificant or erratic because of the acquisition of a weak anhysteretic remanence. Thermal demagnetization reveals a remanence composed of one to three magnetization components with partially to non-overlapping laboratory unblocking temperatures (Fig. 2d, e). The first component removed has steep positive inclination and predominantly north-directed but variable declination. An intermediate to high unblocking temperature component (400–640°C) has south-directed and moderate negative inclination (Hr magnetizations). The characteristic magnetization (ChRM) of the Moenkopi Formation, with dual polarity and shallow inclinations (north-northwest and south-southeast directed) has maximum unblocking temperatures of 690°C. High coercivities suggest that all three magnetizations reside in hematite. Because of the complexity of the NRM, the quality of some demagnetization diagrams is only marginal. In some specimens, the presence of the intermediate unblocking temperature (Hr) magnetization can be inferred by considerable steepening in inclination prior to isolation of the ChRM, whereas in other specimens it is small, poorly defined, or not present (Fig. 2e). At site mo41 (the site closest to the Permian-Triassic unconformity), the ChRM is south-directed and of steep negative inclination. Magnetizations possibly residing in goethite are similar to Gr and Gn magnetizations observed in San Andres strata (Fig. 2f). At the overlying site (mo42), the only component removed is a north-directed magnetization with steep positive inclination and distributed unblocking

TABLE 1. Paleomagnetic data Joyita Hills (primary magnetizations)

		ChRM (in situ)					ChRM (tilt corr.)	
Site	Formation	dec (°)	inc (°)	n	k	$\alpha95$	dec (°)	inc (°)
sa2	San Andres	157.0	-28.5	4	224.9	6.1	148.6	-5.4
sa4	San Andres	355.4	26.1	4	83.5	10.1	344.0	11.8
bf71	Bursum	148.7	-26.9	4	50.1	11.1	150.2	10.8
mo43	Moenkopi	348.8	31.4	5	10.7	25.9	341.4	10.6
mo44	Moenkopi	185.5	-14.0	3	42.5	19.1	182.3	-4.0
mo45	Moenkopi	169.4	4.3	4	26.7	18.1	174.6	22.7
mo48	Moenkopi	173.8	-5.0	4	23.6	19.3	175.3	12.4
mo49	Moenkopi	156.7	8.0	4	10.8	29.3	162.7	30.5
mo52	Moenkopi	136.8	-3.0	2			138.2	23.9

Dec and inc are the mean declination and inclination, respectively. The parameters n, k, and $\alpha95$ are the number of samples used in the calculation and the estimated parameters of Fisherian distributions. The characteristic magnetization (ChRM) is listed in in-situ and tilt corrected (tilt corr.) coordinates.

temperatures between 200° and 600°C.

Isothermal remanence acquisition (IRM) in representative samples of the San Andres Formation do not reach saturation with inductions of 3 Tesla, but hysteresis loops are strongly wasp-waisted, indicating the presence of magnetic phases of low and high coercivity. The IRM acquisition curves are, in these cases, concave upward and show the characteristics of hematite-goethite mixtures (Heller, 1978). This confirms that goethite and hematite are the principal remanence carriers in these rocks. IRM curves of representative samples of the Moenkopi Formation are dominated by hematite contributions, with some evidence of the presence of very small amounts of magnetite, probably of detrital origin. Concave-upward curves in sites mo41 and mo42 indicate that goethite is present. Invariably, when both Gn and Gr magnetizations are present, the first component removed is a small Gn (north-directed and positive) magnetization.

Magnetizations of samples from sites collected from Middle Proterozoic granite at and below the Precambrian-Paleozoic unconformity are of high coercivity and distributed unblocking temperatures of up to 650°C. The ChRM is typically north-directed and of moderate to steep positive inclination (Hn magnetizations). Samples from site jh65, however, gave two groups of magnetizations. A fine-grained felsic dike yields moderate to shallow, northeast-directed magnetizations carried by a phase of low coercivity; coarse-grained granite specimens yield steep negative (Hr) magnetizations of high unblocking temperature (maximum of 650°C) and high coercivity (Fig. 2g). Site jh65 is a few hundred meters below the Precambrian-Paleozoic unconformity.

Line fits for all samples yield MAD (maximum angular deviation) values of less than 15°, with values ranging between 2.6° and 14.8° (averaging 8.4°). Some of the G magnetizations are defined by two points (difference vectors). A shallow, southeast-directed magnetiza tion (or its antipode) was observed in six of the Moenkopi sites (24 samples) and three of the sites collected in upper Paleozoic strata (Table 1). These magnetizations are roughly consistent with the expected Permian-Triassic expected field directions (Fig. 3c). Secondary G and H magnetizations were observed in nearly all sites collected.

PALEOMAGNETIC FIELD TESTS FOR THE TIMING OF REMANENCE ACQUISITION

Intraformational conglomerate test

In a simple positive conglomerate test, the orientations of magnetizations isolated from individual clasts are expected to be randomized by transport and redeposition, but if the magnetization postdates deposition, the clasts are expected to retain magnetizations with similar orientations (Butler, 1992). The small clasts used in this conglomerate test are subrounded and embedded in a tan, coarse-grained sandstone matrix. Clasts are reddish brown and contain more hematite pigment than the matrix. The sharp boundary between clasts and matrix suggests that most of the hematite pigment in the clasts was precipitated prior to deposition. Both clasts and matrix contain large (10–80 μm) grains of specular hematite. These grains show advanced stages of oxidation and are partially dissolved; specular hematite grains are subrounded, and skeletal trellis structures are visible in some. The initial magnetic moment of intra-formational microclasts in the Moenkopi Formation (Fig. 4a) ranges between 10^{-8} and 10^{-10} Am^2, one to three orders of magnitude above the cryogenic magnetometer noise level. We demag-

TABLE 2. Paleomagnetic data for Precambrian, late Paleozoic and Triassic strata, central New Mexico (secondary magnetizations).

	Low T (Gn; in situ)					Low T (Gr; in situ)					High T (Hn; in situ)					High T (Hr; in situ)				High T (Hr; tilt. corr.)		
Site	dec (°)	inc (°)	*n*	*k*	α95	dec (°)	inc (°)	*n*	*k*	α95	dec (°)	inc (°)	*n*	*k*	α95	dec (°)	inc (°)	*n*	*k*	α95	dec (°)	inc (°)
San Andres Fm. (Joyita Hills)																						
sa1	7.0	61.3	3	281	7.4	172.7	-58.1	2			7.3	57.4	4	164.0	7.2							
sa2	10.8	54.4	4	144.7	7.7	168.6	-45.0	3	90.7	13.0												
sa3 (cave)	5.9	54.3	9	115.1	4.8	166.4	-51.2				349.5	55.9	9	56.9	6.9							
sa4	2.9	60.8	6	147.8	5.5											223.1	-57.4	2			163.7	-57.7
sa40						185.6	-50.5	9	88.4	5.5	4.1	60.1	6	47.9	9.8	190.9	-61.0	4	60.9	11.9	146.2	-44.9
sa53						176.7	-57.5	14	77.1	4.6	1.7	58.4	3	92.9	12.9	187.7	-67.5	6	212.5	4.6	137.3	-47.4
San Andres Fm. (Los Pinos Uplift)																						
sa-1p	7.8	61.3	9	73.0	6.1											157.0	-54.7	9	13.9	17.8	175.3	-51.5
San Andres Fm. (Lucero Uplift)																						
sa-luc	10.9	64.1	5	41.3	12.0																	
Moenkopi Fm. (Joyita Hills)																						
mo41	1.3	64.9	5	128.4	6.8	178.2	-53.2	4	38.4	15.0						196.4	-60.7	5	59.7	10.0	164.1	-44.9
mo42-48																179.2	-53.3	7	34.2	10.5	159.4	-33.6
mo42											11.0	62.9	4	727	3.4							
Madera Fm. (Joyita Hills)																						
mf70	358.0	51.2	4	49.8	13.2																	
Precambrian granite (Joyita Hills)																						
jh65																11.6	-84.8	6	19.2	15.7	160.8	-55.7
jh66											17.0	57.4	5	25.3	15.5							
jh67											5.3	61.4	4	66.6	11.3							
jh68											357.0	60.2	5	138.2	6.5							
jh65a (dike)											(57.0	13.2)	8	7.2	22.2							
Mean (in situ)	5.4	59.1	8	209.8	3.8	174.6	-53.6	6	154	5.4	4.0	59.4	8	264.9	3.4	188.2	-65.5	7	22.3	13.1		
Mean (tilt corr.)	339.8	43.7	8	16.6	14	151.7	-32.3	6	75.1	7.8	359.5	37.6	8	12.3	16.5	157.7	-48.6	7	49.0	8.7		

Hr magnetizations, west-central New Mexico (Molina-Garza et al., 1991; 1998b)	In situ				Tilt corrected				
mg (Moenkopi Fm, Lucero uplift)	171.2–53.5	9	120.1	4.7	146.9	-52.4	9	120.1	4.7
sg (Moenkopi Fm, Los Pinos uplift)	152.9–31.7	17	23.4	9.1	163.2	-45.8	17	23.4	9.1
ca (Moenkopi Fm, Lucero uplift)	131.4–28.5	3	67.8	15.1	156.7	-45.7	3	67.8	15.1
fw17 (San Andres Fm, Zuni Uplift)	169.5–57.4	5	143.6	6.4	167.5	-51.5	5	143.6	6.4
fw11 (Chinle Fm, Zuni Uplift)	1634.–61.8	19	32.6	6.0	162.1	-55.9	19	32.6	6.0
Overall mean of Hn	4.0–59.4	8	264.9	3.4	359.5	37.6	8	12.3	16.5
Overall mean of Hr	170.2–59.2	12	14.5	11.8	158.4	-49.4	12	72.6	5.1

Dec and inc are the mean declination and inclination, respectively. The parameters *n*, *k*, and α95 are the number of samples used in the calculation and the estimated parameters of Fisherian distributions. Low (G) and high (H) unblocking temperature magnetizations are identified according to the text.

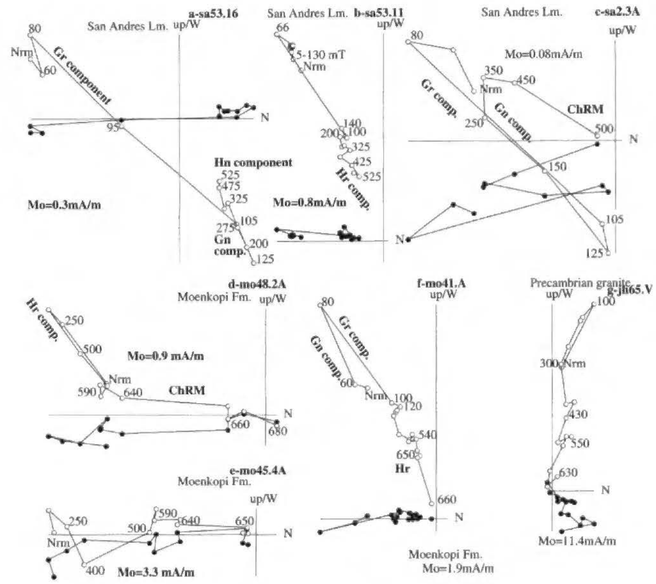

FIGURE 2. Orthogonal demagnetization diagrams (Zijderveld, 1967) of representative samples of the San Andres Limestone (**a–c**), Moenkopi Formation (**d–f**), and Precambrian granite (**g**). Notice that high-coercivity (>130mT) magnetizations of both high (H) and low (G) unblocking temperature in carbonate rocks of the San Andres Formation are south-directed and of steep negative inclination (Hr and Gr) or north-directed and of steep positive inclination (Hn and Gn). A magnetization of moderate negative inclination is also apparent in samples of the Moenkopi Formation (Hr) superimposed on a shallow southeast-directed magnetization (ChRM). A steep negative inclination magnetization is isolated in samples of Precambrian granite. All diagrams are in in situ coordinates. Open (solid) symbols are projections in the vertical (horizontal) plane. Temperatures are in degrees Celsius.

netized a total of 32 microclasts from four independently oriented sample cores. Clasts were extracted from the matrix following the procedure of Geissman et al. (1988). The NRM of the clasts can be univectorial (Fig. 5b) or the sum of two vector components (Fig. 5a–c). A magnetization of distributed unblocking temperatures ranging between 200°C and 600°C is generally south-directed and of shallow inclination (Fig. 5d). A magnetization of high-discrete laboratory unblocking temperature (>600°C) is randomly oriented (Fig. 5e).

The directions of the low and distributed unblocking temperature magnetizations in the small conglomerate clasts are well grouped and resemble the ChRM of Moenkopi strata, indicating that magnetization acquisition continued after deposition (a negative conglomerate test). The fact that magnetizations of south-directed declinations (reverse polarity) are prevalent, suggests, although it does not prove, that the acquisition process did not extend longer than a single polarity interval. In contrast, the high temperature magnetizations in the clasts are scattered and yield a positive conglomerate test, implying that part of the CRM of Moenkopi strata was locked in at an early stage prior to incorporation of the clasts in the conglomerate. Specular hematite grains are the likely carriers of the high unblocking temperature magnetization in the microconglomerate clasts and the characteristic magnetization of Moenkopi strata.

Eocene conglomerates

The Baca Formation consists of coarse-grained sandstone and thick, laterally continuous layers and lenses of boulder-size conglomerate. We collected 42 samples from 29 clasts of hematite-cemented sandstone (ba46) and carbonate rocks (ba50). Clasts of the Moenkopi Formation can be generally recognized because of their characteristic purplish red color. The limestones of the San Andres Formation are also distinct from Pennsylvanian limestones in that San Andres rocks typically lack fossils and are greenish-gray and tan in color.

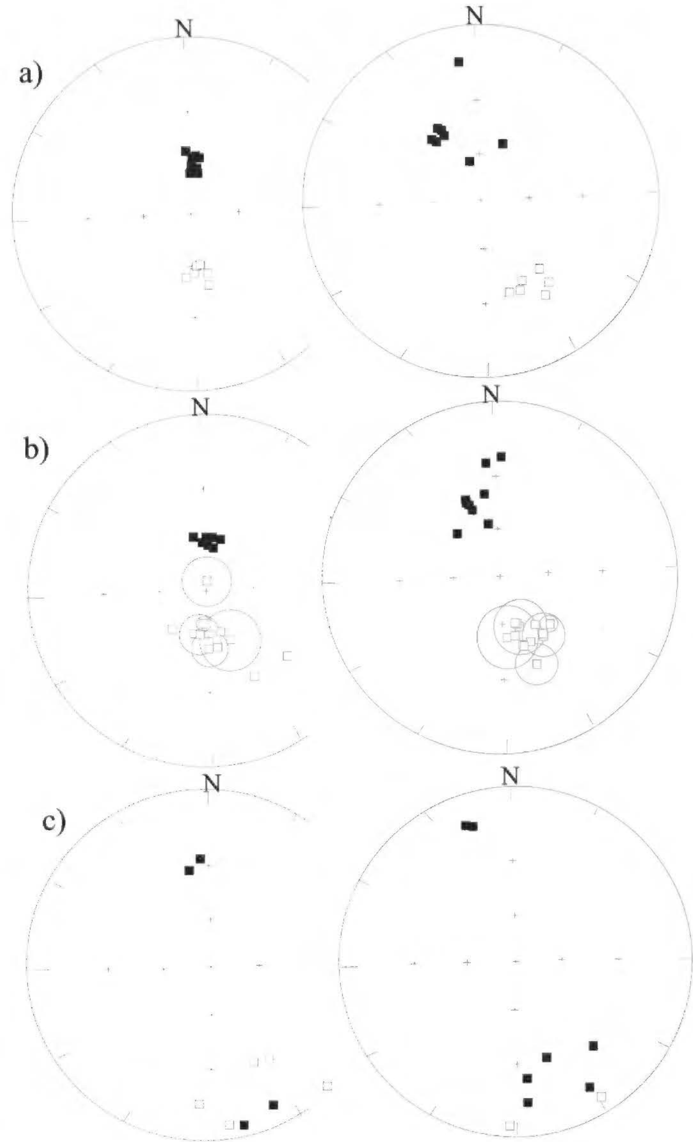

FIGURE 3. Equal-angle stereographic projections of magnetizations isolated in the Joyita Hills. Open (closed) symbols are projections on the upper (lower) hemisphere; **a**, G magnetizations in in situ and tilt corrected coordinates; **b**, H magnetization in in situ and tilt corrected coordinates (Hr site from the Joyita Hills include (95 cones of confidence, other data are from Molina-Garza et al. (1991 and 1998b)); **c**, primary magnetizations in Triassic and upper Paleozoic strata.

For Moenkopi clasts, thermal demagnetization reveals that the NRM is univectorial and of high (>600°C) laboratory unblocking temperature or, more often, the sum of an intermediate (200–600°C) and a high (>600°C) laboratory unblocking temperature magnetization (Fig. 6a, b). The lower unblocking temperature magnetization of some of the clasts plots near the recent field direction. Otherwise, directions for both magnetizations observed in sandstone clasts are scattered (Fig. 6f), suggesting positive conglomerate tests for both the intermediate and the high unblocking temperature magnetizations. For clasts that contain well-defined internal bedding, magnetizations referred to the bedding plane are of predominantly shallow inclination and random declination, indicating a robust positive conglomerate test (Fig. 6g).

Limestone clasts (ba50) contain weak magnetizations of low unblocking temperature (<250°C; Fig. 6c) and low coercivity, with some clasts revealing intermediate unblocking temperature (200–500°C) magnetizations (Fig. 6e). Low unblocking temperature

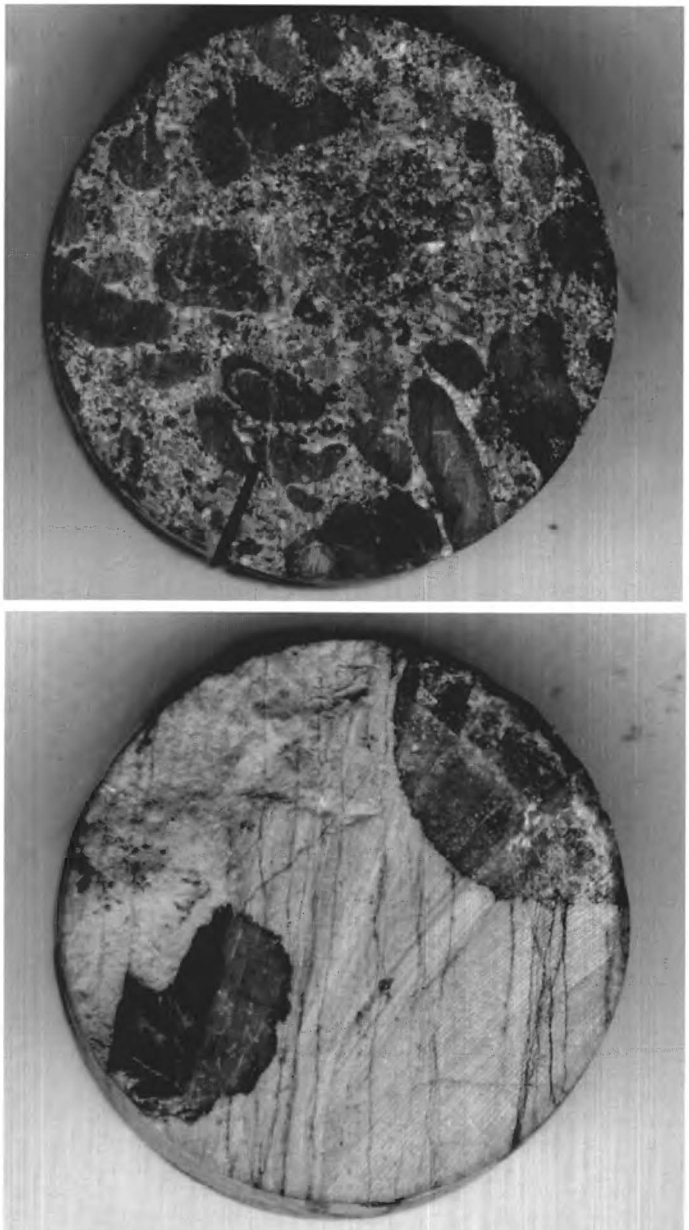

FIGURE 4. **(Upper)** Digital image of a cross-section of a paleomagnetic core (2.5 cm in diameter) from intraformational conglomerate in the Moenkopi Formation. **(Lower)** Digital image of a cross-section of a paleomagnetic core of limestone of the San Andres Formation showing hematitic veinlets and nodules.

magnetizations are north directed and of steep positive inclination, consistent with acquisition of a recent viscous remanence. Hematite and/or goethite carry a similar magnetization because end-point vectors for samples subjected to AF demagnetization to 80 mT are north- to northeast-directed and of steep positive inclination. This result suggests a robust negative conglomerate test that confirms our interpretation of Gn magnetizations as magnetizations of recent origin. The small number of magnetizations of intermediate unblocking temperature are insufficient for a statistically significant conglomerate test, but appear to be scattered. Despite the fact that Gr and Hr magnetizations are widespread near the Permian-Triassic unconformity and may dominate the NRM, they were not observed in Permian and Triassic clasts in the Baca conglomerate.

INTERPRETATION

ChRMs in the Moenkopi Formation resemble the expected Middle

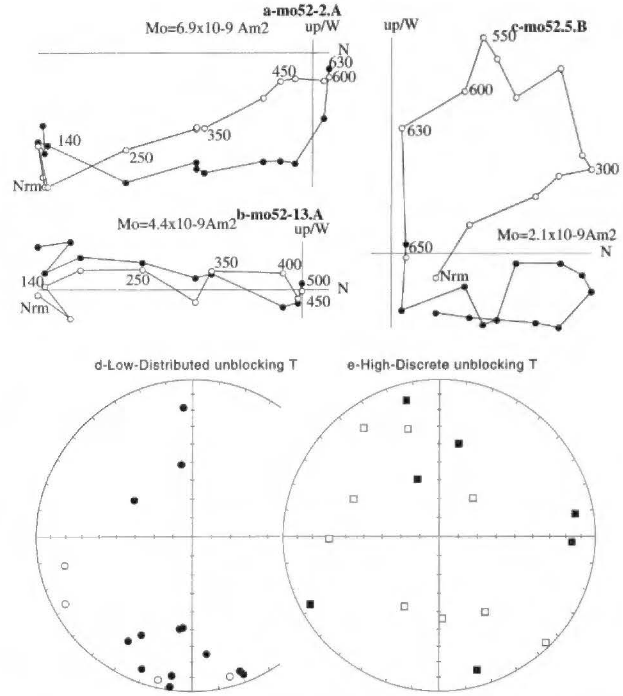

FIGURE 5. Results of a conglomerate test on intraformational clasts in the Moenkopi Formation. Orthogonal demagnetization diagrams (**a–c**) of selected clasts showing distributed unblocking temperature magnetizations; **d**, equal-area projection of south-directed and shallow, low unblocking temperature magnetizations; **e**, equal-area projections of high-unblocking temperature magnetization (>600°C). Symbols as in Figures 2 and 3.

Triassic direction of North America and the site mean of red beds of the Lower Permian Bursum Formation, and two sites in the San Andres limestones resemble the expected late Paleozoic field direction. These are interpreted as primary magnetizations, but the number of sites, in both cases, is insufficient for paleomagnetic pole determinations. Furthermore, within- and between-site scatter are relatively large, possibly reflecting the small number of samples per site.

For the San Andres Formation, negative conglomerate and tilt tests suggest that north-directed magnetizations can be readily interpreted as VRMs or CRMs of late Tertiary (post-Baca Formation) or Quaternary age. For only those samples demagnetized with AF before low-temperature thermal demagnetization, can north-directed magnetizations carried by goethite be positively distinguished from a VRM residing in magnetite. Based on a negative tilt test and the fact that their overall mean is indistinguishable from G magnetizations, Hn magnetizations are also interpreted to be of recent origin, but maximum unblocking temperatures of 650°C are inconsistent with a viscous origin of this magnetization (Pullaiah et al., 1975; Walton, 1980).

Hr magnetizations have been recognized in Permian strata in which primary sedimentary structures are modified by the replacement of gypsum layers and nodules by hematitic cement and at places pervasively invaded by hematite-rich veinlets (Fig. 4b), supporting the hypothesis that these magnetizations are, indeed, secondary. Nevertheless, the virtual absence of Hr magnetizations in limestone and red sandstone clasts of the Baca Formation suggests that acquisition occurred prior to Eocene time. In rocks containing Gr and Hr magnetizations, these form statistically distinct groups in both in-situ and tilt-corrected coordinates. For Gr magnetizations, the precision parameter in tilt-corrected coordinates decreases by a factor of two with respect to the in situ calculation, suggesting that magnetizations postdate tilt. For Hr magnetizations in the Joyita Hills the opposite is true, but this result depends heavily on whether or not site jh65 in Precambrian granite is included. If this site is left out, the in situ and tilt-corrected means show the same

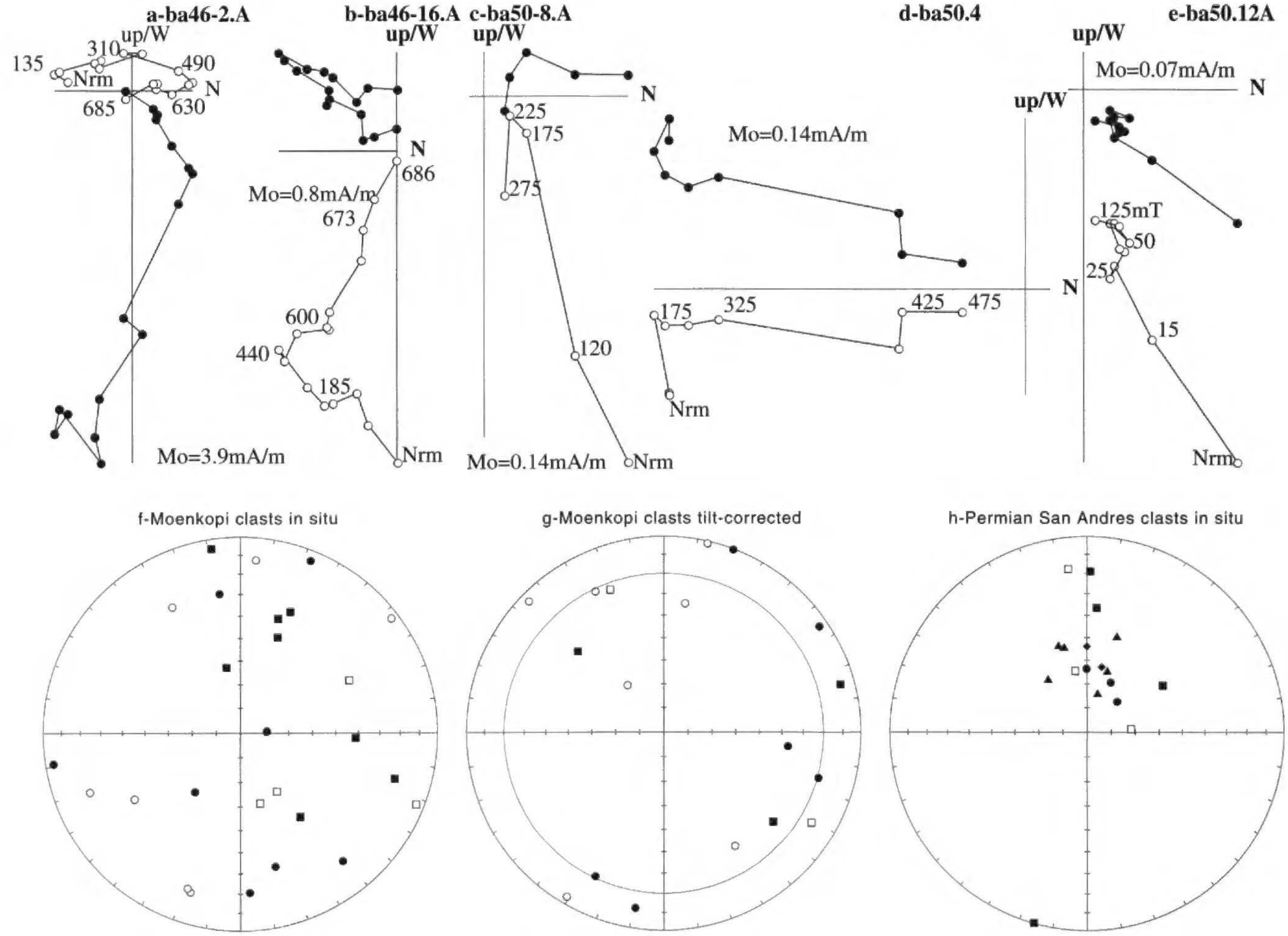

FIGURE 6. Orthogonal demagnetization diagrams of Moenkopi red sandstone clasts (**a**, **b**) and San Andres limestone clasts (**c–e**) in the Baca Formation. Normally two magnetizations are present in the sandstone clasts, a low and distributed unblocking temperature magnetization (squares in **f** and **g**), and a high unblocking temperature magnetization (circles in f and g). Both of these components are randomly distributed. Furthermore, for clasts with well-defined internal bedding, tilt-corrected directions (g) are predominantly of shallow inclination, as expected if acquisition of this magnetization was early, indicating a robust positive conglomerate test. Notice the virtual absence of Hr magnetizations in Moenkopi clasts. For clasts of the San Andres limestones, magnetizations are well grouped near the expected late Tertiary or Quaternary field direction (**h**). Triangles refer to magnetizations of low unblocking temperature and low coercivity, circles are end-point vectors of samples subjected to AF demagnetization, squares are magnetizations of intermediate unblocking temperature, and the recent dipole field direction is plotted as a diamond.

degree of scatter, and we cannot determine the timing of remanence acquisition with respect to structural deformation. Nevertheless, if the data from the Joyita Hills are combined with results from other localities in western and central New Mexico (Table 2), the tilt-corrected site means are better grouped and the improvement in the overall mean yields a statistically significant tilt test, with the precision parameter k increasing by a factor of five (Fig. 3b). Hr magnetizations are thus interpreted to predate structural deformation in the region which may include a component of Laramide tilt (Beck, 1991). The overall mean, including 12 sites, is Dec = 158.4° and Inc = -49.4°.

DISCUSSION

In the context of the debate over the timing of remanence acquisition in red beds, results of an intraformational conglomerate test are consistent with the model of "syn- or near-depositional" remanence acquisition of Purucker et al. (1980) for the high-discrete unblocking temperature ChRM of Moenkopi red beds. The conglomerate test shows, however, that CRM acquisition continued after deposition, as a remanence of low and distributed unblocking temperature was acquired. We speculate that if the "primary" CRM residing in specular hematite was of low intensity, a "post-depositional" CRM may completely obliterate the paleomagnetic record and make polarity stratigraphy of little use, thus supporting the model of "long-term remanence acquisition" of Larson et al. (1982).

Two main factors can affect the reliability of a CRM in red beds: the original abundance of specular hematite grains carrying a "primary" CRM, and the availability of Fe^{2+} and Fe^{3+} for the continuing precipitation of secondary fine-grained hematite (and a "post-depositional" CRM). The process will be regulated by the availability of oxidizing fluids, the rate of reversals of the magnetic field, and the size achieved by authigenic hematite crystals. A fast reversal rate may result in acquisition of aberrant intermediate directions, as has been observed in some previous studies (Molina-Garza et al., 1991; C. McCabe, personal commun., 1986).

The paleomagnetic data derived from Hr secondary magnetizations from 12 sites, including 5 from the Joyita Hills and 7 from other localities (Table 2), yield a mean pole at 71.4°N–157.9°E. Previous study of Triassic strata in central New Mexico suggests that areas in the Rio Grande rift have experienced a small but geologically appreciable clockwise rotation of about 5° relative to cratonic North America, but it is unclear if this area rotated rigidly with the Colorado Plateau or via an independent mechanism (Molina-Garza et al., 1991). We propose that localities where the Hr magnetizations have been observed require a small correction similar to that for the Colorado Plateau (Molina-Garza et al., 1998a). The corrected pole position (5° using a rotation pole is at 34°N 105°W) is 67.3–161.7°E.

Few means to determine accurately the timing of acquisition of Hr magnetizations exist. Positive conglomerate and tilt tests indicate that it is pre-Eocene, and observed paleomagnetic inclinations (I = 49°) suggest an age younger than Middle Jurassic. The argument can be made that Hr magnetizations are post-Middle Jurassic because Middle Jurassic sandstone dikes in the lower Summerville Formation in west central New Mexico yield magnetizations with a mean of D = 163°, I = -46 (n = 33 samples) (Geissman et al., 1990), indistinguishable from Hr magnetizations observed at the Permian-Triassic unconformity. Magnetizations in the Summerville Formation are interpreted to be secondary (Geissman et al., 1990) because the remanence in the cross-cutting sandstone dikes is identical to that in the host strata.

Previously, Hr magnetizations have been genetically linked to Laramide-style deformation that affected this region in early Tertiary time (Molina-Garza et al., 1991). Also, Jackson and Van der Voo (1986) identified a south-directed magnetization of moderate negative inclination in the lower Paleozoic El Paso and Montoya formations of south-central New Mexico, and interpreted it to be associated with Late Cretaceous–early Tertiary deformation. A problem with that interpretation for Hr magnetizations in central New Mexico is that inclinations observed (~49°) are significantly shallower than expected for the Late Cretaceous (~56°). The magnetization in the rocks studied by Jackson and Van der Voo (1986) is interpreted as a CRM residing in magnetite that post-dates folding, but a fold test is inconclusive, and a reliable pole position could not be determined because of incomplete separation of the magnetization. The paleomagnetic pole for Hr magnetizations obtained in this study is statistically indistinguishable from Late Jurassic poles of the Morrison Formation (Bazard and Butler, 1994). These authors have suggested that in the Late Jurassic, the North American paleomagnetic pole tracked from a late Callovian–Oxfordian position at about 60°N–135°E (the Summerville Formation of eastern Utah and northern Arizona) to a late Tithonian position at about 68°N–156°E (the Brushy Basin Member of the Morrison Formation of western Colorado and eastern Utah).

For the acquisition of a prominent overprint such as the Hr component in Triassic and Permian strata in central New Mexico, it would appear that an influx of oxidizing fluids may produce a secondary "late" CRM with some characteristics of a post-depositional "long-term" CRM. Rocks near the disconformity were subject to a long episode of weathering. This very likely plays a role in the availability of Fe^{2+} and Fe^{3+} for the precipitation of secondary hematite and acquisition of Hr magnetizations. The occurrence of dual-polarity secondary magnetizations residing in goethite suggests that the P-Tr disconformity remains a preferred pathway for migrating fluids. It is likely that a similar process has produced secondary CRMs of recent origin residing in hematite (Hn) along the Precambrian-Paleozoic unconformity.

CONCLUSIONS

Permian and Triassic strata of the San Andres and Moenkopi formations in central and western New Mexico contain secondary magnetizations residing in goethite and hematite. A magnetization residing in hematite is ancient and predates structural deformation. Twelve site means define a paleomagnetic pole at 71.4°N, 157.9°E, falling along the Late Jurassic segment of the North American apparent polar wander path; thus the timing of remanence acquisition is inferred to be Late Jurassic. The close association of CRM acquisition with the Permian-Triassic disconformity suggests that migration of oxidizing fluids (channeled along it) may have played an important role in precipitation of secondary hematite. Results from intraformational conglomerate clasts in red beds of the Moenkopi Formation indicate that a high and discrete unblocking temperature magnetization was locked in at an early stage, prior to incorporation of the clasts in the conglomerate, but the acquisition of a low and distributed unblocking temperature magnetization of predominantly reverse polarity continued after deposition.

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