# *Paleomagnetism and mangetostratigraphy of the Upper Triassic Petrified Forest and Poleo formations, north-central New Mexico, and the Bluewater Creek and Lower Petrified Forest Formations, central New Mexico*

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# PALEOMAGNETISM AND MAGNETOSTRATIGRAPHY OF THE UPPER TRIASSIC PETRIFIED FOREST AND POLEO FORMATIONS, NORTH-CENTRAL NEW MEXICO, AND THE BLUEWATER CREEK AND LOWER PETRIFIED FOREST FORMATIONS, CENTRAL NEW MEXICO

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**Abstract.**—As demonstrated by vertebrate biostratigraphy and palynostratigraphy, the Upper Triassic Chinle Group spans most of the Late Triassic. The Chinle Group was deposited by a fluvial system and consists predominantly of red to purple mudstones with some red to orange siltstones and red to buff sandstones. In the Chama basin, north-central New Mexico, both lower and upper Chinle Group strata are well-exposed and are being used to develop a more complete magnetic reversal chronology for the Late Triassic for the American Southwest. Our sampling methods concentrate on hematitic mudrocks, using an intricate block sampling technique. These materials typically carry a well-defined, well-grouped magnetization dominated by pigmentary hematite that is unblocked below about 660ºC. For example, a single horizon (level 39) in the Painted Desert Member of the Petrified Forest Formation yields an estimated site mean of D=172.9º, I=7.0º, $\alpha_{95}$=5.5º and *k*=102.5 (N = 8 independent samples). Indurated, coarser-grained deposits are sampled by more conventional methods. Sandstones and siltstones of the Poleo Formation contain both detrital and authigenic hematite and some detrital magnetite as the magnetization carriers and typically yield a well-defined magnetization at the site (single bed) level (e.g., site 11, eight independent samples, yields an estimated site mean of D=187.4º, I=0.8º, $\alpha_{95}$=3.4º and *k*=268.1). A very preliminary polarity reversal stratigraphy has been developed for the Poleo and Petrified Forest formations in the Chama basin. The Petrified Forest Formation includes multiple polarity intervals. All accepted sites in the Poleo Formation are of reverse polarity. The upper part of the Bluewater Creek Formation and lower Blue Mesa Member (Petrified Forest Formation) in the Zuni Mountains, central New Mexico, appear to be entirely of reverse polarity.

## INTRODUCTION

The Late Triassic was a critical juncture in Earth history in terms of vertebrate evolution, tectonics and climate. During the Late Triassic, several important vertebrate groups arose, including mammals, dinosaurs, pterosaurs and turtles. Within the same time frame, Pangea began to rift around the present day Gulf of Mexico, and the climate transitioned from the colder conditions of the Permian to the global greenhouse of the mid to late Mesozoic. These global-scale dramatic changes make it imperative to be able to globally correlate Upper Triassic strata, to better understand the timing of vertebrate evolution as well as tectonic and climatic changes.

The Upper Triassic Chinle Group, prominent in the Mesozoic stratigraphy of the American Southwest (Fig. 1), was deposited by a large fluvial system. Based on vertebrate biostratigraphy and palynostratigraphy, the Chinle Group is inferred to span most of the Late Triassic (Litwin, 1986; Lucas and Hunt, 1992; Hunt and Lucas, 1993; Lucas et al, 2003). Until recently, the many paleomagnetic studies of Chinle Group strata have focused on readily sampled materials (i.e. drillable sandstones and siltstones) (e.g., Reeve, 1975; Reeve and Helsley, 1972; Molina-Garza et al., 1993, Steiner and Lucas, 2000). Thus, most strata of the Chinle Group , which consist of mudstones and claystones, have been ignored. Efforts to construct a stratigraphically continuous magnetic polarity chronology for the Chinle Group have primarily involved independent sections of Chinle strata from different basins and outcrop belts that have been stitched together based on lithologic correlations.

Our current efforts in the Chama basin (Fig. 1) have focused on sampling the fine-grained components of the Chinle Group at Coyote Amphitheater (a complete and continuous exposure of the Chinle Group) and at Abiquiu Dam. These rocks have yielded, overall, very high quality results. The principal focus of this research has been to develop as complete a magnetostratigraphy as possible for the Chinle Group in the Chama basin. Sufficient sampling at each stratigraphic level was conducted to provide a robust evaluation of the paleomagnetism of these rocks.

In addition to the Chama basin sequence, we have also examined an additional Chinle section in the Zuni Mountains (central New Mexico), consisting of the upper Bluewater Creek Formation and the lower Blue Mesa Member (Petrified Forest Formation). With these data we will test cross-correlation between basins,

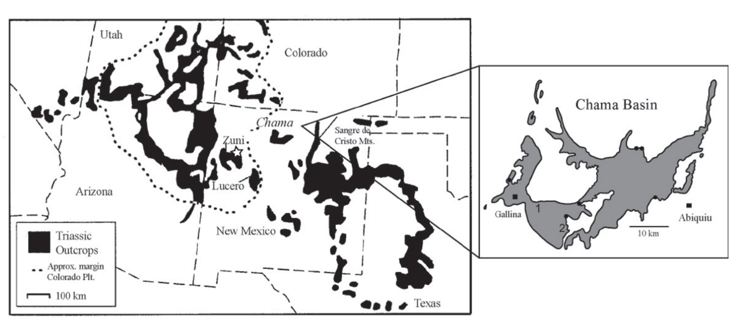


FIGURE 1. Distribution of Triassic outcrop area (approximates outline of Chinle basin) (from Molina-Garza et al., 1993), with expanded view of Chama basin Chinle Group outcrops. 1 = Abiquiu Dam, 2 = Coyote Amphitheater, star = Zuni Mountains.

as well as tie the magnetostratigraphy of these rocks to a tuffaceous, zircon-bearing sandstone within the section for which we are obtaining a high-precision U-Pb zircon age. Here we present preliminary magnetostratigraphic data from the mudstone-dominated Petrified Forest Formation and the Poleo Sandstone, as well as the Bluewater Creek Formation and Blue Mesa Member (Petrified Forest Formation), of the Chinle Group.

## GEOLOGIC SETTING AND STRATIGRAPHY

The Chinle Group was deposited in a back-arc basin in western Pangea by a large and widespread fluvial system (Stewart et al., 1972; Blakey and Gubitosa, 1983; Dubiel, 1987) and consists predominantly of red mudstones, with lesser orange siltstones and buff sandstones. Upper Triassic strata in the Chama basin of north-central New Mexico have been assigned to six formations (in ascending order): Zuni Mountains (=mottled strata), Shinarump (=Agua Zarca), Salitral, Poleo, Petrified Forest and Rock Point formations (Lucas and Hunt, 1992; Hunt and Lucas, 1993a,b; Lucas et al., 2003) (Fig. 2). We briefly describe those formations sampled for this study.

The Poleo Formation consists primarily of sandstones but intrabasinal calcrete and mud-clast conglomerates are more prevalent in the lower third of the unit (Fig. 2). Clasts in the conglomerate beds are mudstone or siltstone rip-ups, calcrete nodules, and occasionally carbonized plant debris. Both the sandstones and conglomerates contain authigenic hematite cement in variable abundance. The sandstones' dominant bedform is trough crossbedding, and they are micaceous litharenites and subarkoses, indicating a lack of compositional maturity (Lucas et al., 2003 and references therein). Most Poleo rocks are dusky yellow to grayish yellow. The formation lies disconformably above the Salitral Formation and conformably below the Petrified Forest Formation. It is thickest at Abiquiu Dam, where over 53 m of section is exposed in the side walls of the canyon below the dam.

The Petrified Forest Formation is the thickest and most widespread part of the Chinle Group (Repenning et al., 1969). It is predominantly a reddish brown bentonitic mudstone, although it includes thin beds of arkosic sandstones (Dubiel, 1987, 1989) and rip-up clast conglomerates (Zeigler, 2002, 2003; Tanner et al., 2003) (Fig. 2). The mudstones are mottled at distinct stratigraphic levels, which represent paleosol formation (Tanner, 2003). Overall, the Petrified Forest Formation has been interpreted as floodplain deposits (Lucas et al., 2003 and references therein). Vertebrate fossils found in the Petrified Forest Formation indicate a Revueltian (early to mid-Norian) age (Lucas, 1993, 1998).

In the Zuni Mountains, similar Upper Triassic strata are exposed and have been assigned to the following formations (in ascending order): Zuni Mountains, Shinarump, Bluewater Creek, Sonsela and Petrified Forest. The Bluewater Creek Formation has three distinct lithofacies (Heckert and Lucas, 2003): interbedded mudstones and siltstones with scattered calcrete horizons that are interpreted as overbank/floodplain deposits, ripple laminated to plane bedded sandstones with minor intraformational conglomerates that are interpreted as low sinuosity fluvial deposits, and

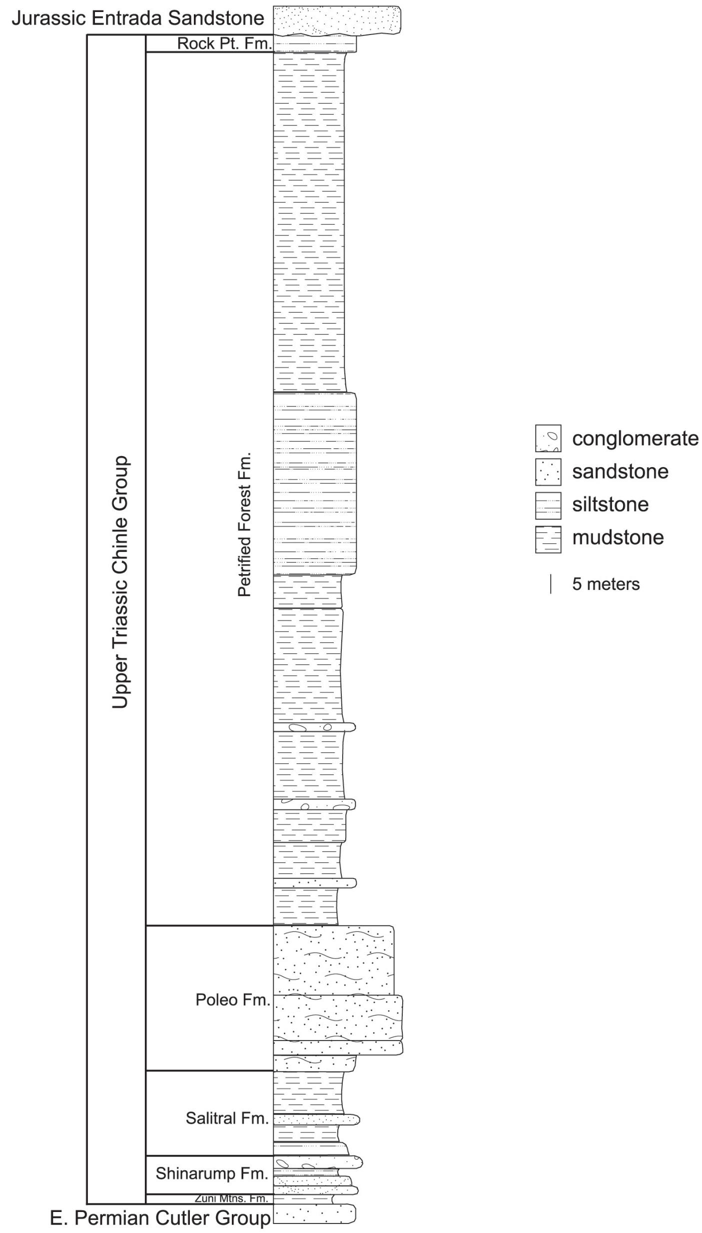


FIGURE 2. Generalized stratigraphic column of the Chinle Group in northern New Mexico. Note Zuni Mountains Formation is only locally present.

greenish bentonitic mudstones and black shales that have been interpreted as lacustrine.

At Six Mile Canyon in the Zuni Mountains, strata of the Bluewater Creek Formation are predominantly the first of these lithofacies (Fig. 2). The contact between the Bluewater Creek Formation and the overlying Petrified Forest Formation is marked by a white, tuffaceous sandstone that is the lowest unit of the Blue Mesa Member (Heckert and Lucas, 2003). The rest of the Blue Mesa Member strata at Six Mile Canyon consists of mudstones with common, discontinuous horizons of calcrete nodules. The Blue Mesa Member has been interpreted as floodplain deposits with paleosol horizons (Heckert and Lucas, 2003).

## SAMPLING AND METHODS

We sampled sub-horizontal Poleo strata at Abiquiu Dam (36.2ºN, 106.2ºW), with a stratigraphic spacing of about 2 m between each site (32 total sampled sites). In the upper part of the Poleo Formation, this sampling interval was dictated by bed thickness, so that each site is a discrete bed, whereas parts of the lower third of the section had large-scale bedding and some beds included several sites. At each site, 6 to 8 samples were typically drilled and oriented in the field. Most samples could be prepared into multiple specimens for demagnetization.

Petrified Forest Formation strata were sampled at Coyote Amphitheater (36.1ºN, 106.4ºW), where strata dip 18º to the west, using an initial sampling interval of about 5 m, for a total of 40 sampling sites. Fresh, in situ mudrock was exposed by digging at least a half meter into the outcrop. We used an intricate block sampling method where individually oriented blocks were carved out in the field and then dry-cut into oriented, ~2 $cm^3$ cubes (e.g., Johnson et al., 1975) (Fig. 3). At each site, typically six to seven blocks were removed, each of which yields from one to seven or more individual specimens. Progressive thermal demagnetization was applied to most specimens to investigate the character of the natural remanent magnetization (NRM) in these materials.

Bluewater Creek Formation and Blue Mesa Member strata were sampled at Six Mile Canyon (35.4ºN, 108.5ºW) at about 1 m intervals above and below the white, tuffaceous sandstone at the base of the Blue Mesa Member for a total of 10 sampling sites. As at Coyote Amphitheater, we used the block sampling method described previously to sample mudrocks. At each site five to eight blocks were removed, with each block yielding from one to eight individual specimens.

All measurements of the natural remanent magnetization (NRM) were made using a 2G Enterprises Model 760R superconducting rock magnetometer, equipped with DC SQUIDS, with a magnetic moment noise level of less than $1.0 \times 10^{-6}$ A/m. At least one specimen per sample was subjected to progressive thermal demagnetization, using either a Shaw MMTD or an ASC 48 thermal demagnetizer . Where possible for sandstones, duplicate specimens were subjected to chemical demagnetization, essentially following the procedures of Henry (1979). Progressive demagnetization data were analyzed using the principal component analysis approach (Kirschvink, 1980) with sequences of demagnetization data typically unanchored to the origin; individual linear segments were accepted if maximum angular deviation (MAD) values were less than 10º. Where data were anchored to the origin, we only accepted results if MAD values were less than 15º.

Acquisition of isothermal remanent magnetization (IRM) to saturation (SIRM) and backfield DC demagnetization of SIRM experiments were conducted using a home-built pulse magnetizer that provided a DC field up to 2.97 T, which is capable of saturating most assemblages of hematite grains. Thermal demagnetization of IRM acquired in DC fields of 2.97 T, 0.3 T and 0.03 T, along three orthogonal axes (Lowrie, 1990), was conducted on representative specimens to further evaluate the magnetic mineralogy.

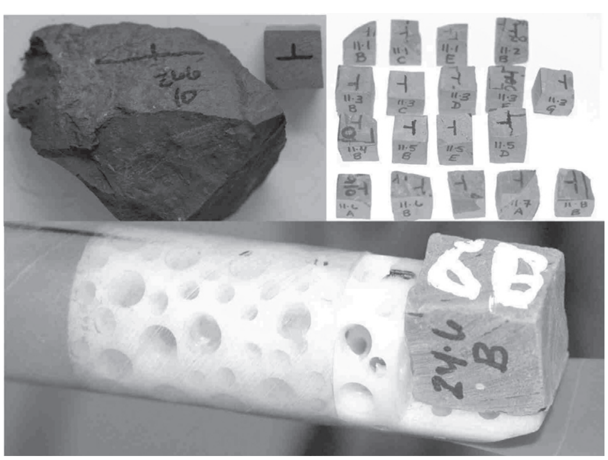


FIGURE 3. Preparation and measurement of "cube" specimens (cubes are about 2 $cm^3$). A. Oriented mudstone sample with one cube from sample from same level. B. Cubes from Coyote Amphitheater level 11. C. Single cube from Coyote Amphitheater level 24 mounted on nonmagnetic (Delrin) holder, ready for insertion into magnetometer.

## PALEOMAGNETIC RESULTS

### Poleo Formation, Abiquiu Dam

Samples from most sites in horizontal strata of the Poleo Formation yield relatively well-defined (Fig. 4a-d) and well-grouped magnetizations (Fig. 4e) that are of reverse polarity (south-seeking and very shallow inclination). We accepted site mean directions from 21 of 30 sites analyzed to date (Appendix), and these yield a grand mean direction of D = 182.7°, I = -0.3°, $\alpha_{95}$ = 5.3° and $k$ = 36.5 (Fig. 4e). Samples from several sites reveal totally incoherent demagnetization behavior with nonlinear decays and random directions (e.g., Fig. 4b)–in some cases, this response is readily explained by the presence of abundant to occasional light green-gray (reduced Fe) mudstone rip-up clasts. For sites yielding interpretable results, duplicate specimens subjected to chemical demagnetization show an 80 percent decrease in intensity of magnetization, after immersion to 370 hours total, with no appreciable change in their direction (Fig. 4d). This response is interpreted to indicate that fine-grained pigment hematite, as an authigenic, grain-coating phase, is an important remanence carrier in these rocks.

Results of three-component thermal demagnetization of IRM show the variable character of the magnetic properties of Poleo strata. In most samples, the highest coercivity component dominates the magnetization response (e.g., samples 10H, 11B, Fig. 5) and shows maximum unblocking temperatures well above 650°C, while in others the intermediate and even low coercivity components are the most intense (e.g., samples 17G, 18B, Fig. 5). In all cases, the low coercivity component has most of its magnetization unblocked by 580°C, indicating the presence of minor amounts of magnetite. Those sites characterized by the dominance of the high coercivity component yield the highest-quality, most interpretable demagnetization results and the best defined site mean directions.

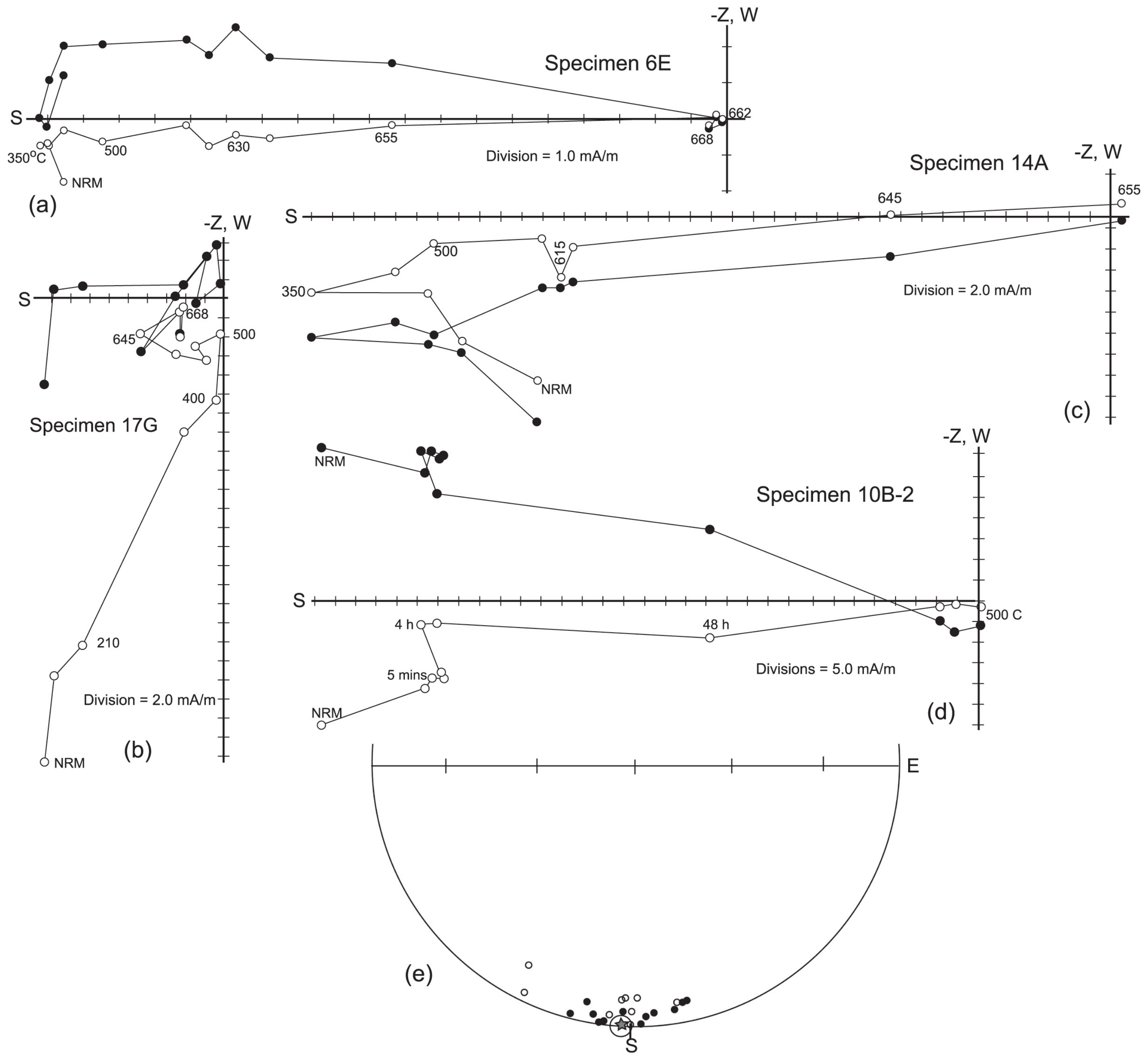


FIGURE 4. Examples of response to progressive thermal (a-c) and chemical (d) demagnetization, specimens from samples of Poleo Formation strata. Orthogonal demagnetization diagrams (Zijderveld, 1967) showing the simultaneous projection of the horizontal (N-S vs. E-W) component of the magnetization (filled symbols) and the vertical (N-S vs. -z,+z) component of the magnetization (open symbols). For thermal demagnetization, peak demagnetizing temperatures are given beside vertical projection data. For chemical demagnetization, the total number of hours (cumulative) of leaching in HCl for each specimen is given beside the vertical projection. (e) Partial equal area projection showing site mean and grand mean direction for accepted sites from Poleo strata. Closed (open) symbols refer to lower (upper) hemisphere projections.

**Petrified Forest Formation, Coyote Amphitheater**

Specimens from most stratigraphic levels in mudstones of the Petrified Forest Formation have also yielded relatively well-defined (Fig. 6a-e) and well-grouped magnetizations (Fig 6f). We accepted site mean directions from 17 of 23 analyzed sites (Appendix) and these yield a total population in situ (geographic coordinates) grand mean direction of D = 177.3°, I = 7.5°, $\alpha_{95}$ = 6.5° and $k$ = 23.5 (Fig. 6d). The normal polarity grand mean direction is D = 359.7°, I = 3.2°, $\alpha_{95}$ = 14.3° and $k$ = 15.9 and the reverse polarity grand mean direction is D = 176.7°, I = 9.9°, $\alpha_{95}$ = 7.2° and $k$ = 31.1, with these sites passing a reversal test. At least one site yielded mixed polarity results, which may be the result of pedogenic modification of that horizon. Results of three

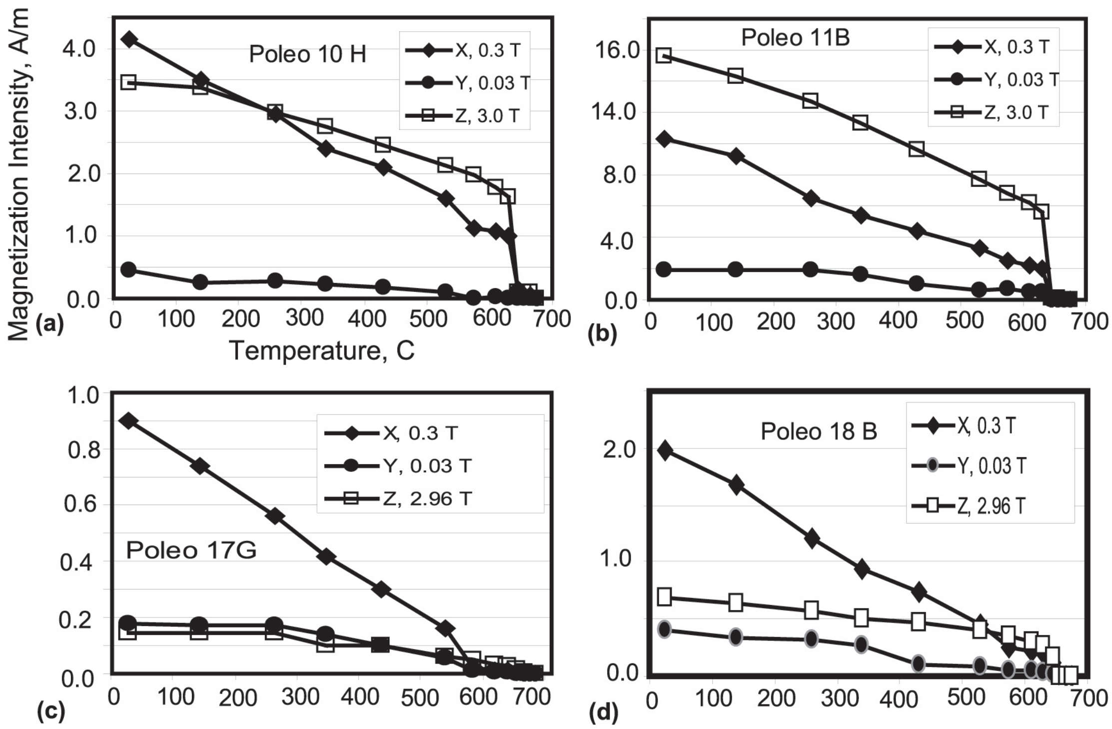


FIGURE 5. Plots showing thermal demagnetization response of Poleo Formation (Abiquiu Dam) samples to IRM acquired along three different axes in progressive thermal demagnetization following the method of Lowrie (1990).

component thermal demagnetization of IRM experiments (Fig. 7) show that the high coercivity component dominates the magnetization signal, and is fully unblocked well above 650°C, indicating that hematite is the dominant magnetic carrier. Importantly, the intensity of the lower coercivity components is typically at least one order of magnitude below that of the highest coercivity component.

### Six Mile Canyon, Zuni Mountains

Samples from seven 7 of the 10 sampled sites yielded well-defined and relatively well-grouped magnetizations of predominantly reverse polarity (Figure 8a-d). The seven accepted sites provide a resulting grand mean direction of D = 177.6°, I = -3.0°, $\alpha_{95}$ = 10.4° and $k$ = 34.5 (Fig. 8e). Two of the three sites that were not included reveal mixed polarity magnetizations with moderate to steep inclinations. One of these sites, site 4, which is immediately below the tuffaceous sandstone, has clearly been subjected to intense pedogenic modification. Mudstones from this section yield similar behavior in three component thermal demagnetization studies (Fig. 9), with the high coercivity component predominating.

## DISCUSSION

Chinle Group strata in the Chama Basin and Zuni Mountains, overall, provide what we interpret to be Late Triassic age magnetizations, of primary to near-primary origin, that appear to be faithful and relatively high fidelity recorders of a Late Triassic field. These results are considered Late Triassic because they are distinct from potentially Jurassic-age or younger magnetizations (e.g. results from Molina-Garza et al., 2003), and strata subjected to pedogenesis have no coherent remanent magnetizations. Poleo Formation strata at Abiquiu Dam yield well-defined magnetizations of almost exclusively reverse polarity (Fig. 10). Response by these rocks to chemical demagnetization is interpreted to indicate that fine-grained pigment hematite, as an authigenic, grain-coating phase, is an important remanence carrier in these rocks. Throughout the Chama basin, the Poleo Formation varies considerably in thickness, from a few meters to over 50 m thick at the dam. The apparent absence of reversals in this section implies that the entire Poleo section was deposited during a brief time interval, given that reversals of the magnetic field during the Late Triassic were relatively frequent (as evidenced by the Newark Supergroup magnetostratigraphy, Olsen et al., 1996, 2002).

The Petrified Forest Formation at Coyote Amphitheater shows both normal and reverse polarity magnetizations, with, to date, a predominance of reverse polarity in the section (Fig. 10). At this time, we have not analyzed all of the sites sampled and with further, considerably more detailed analysis, it is entirely possible that a greater reversal frequency will be seen in this section (especially in light of the coarseness of the currently used sampling interval).

The Six Mile Canyon section in the north-central Zuni Mountains, which to date demonstrates entirely reversed polarity (Fig. 10), includes the contact between the Bluewater Creek Forma-

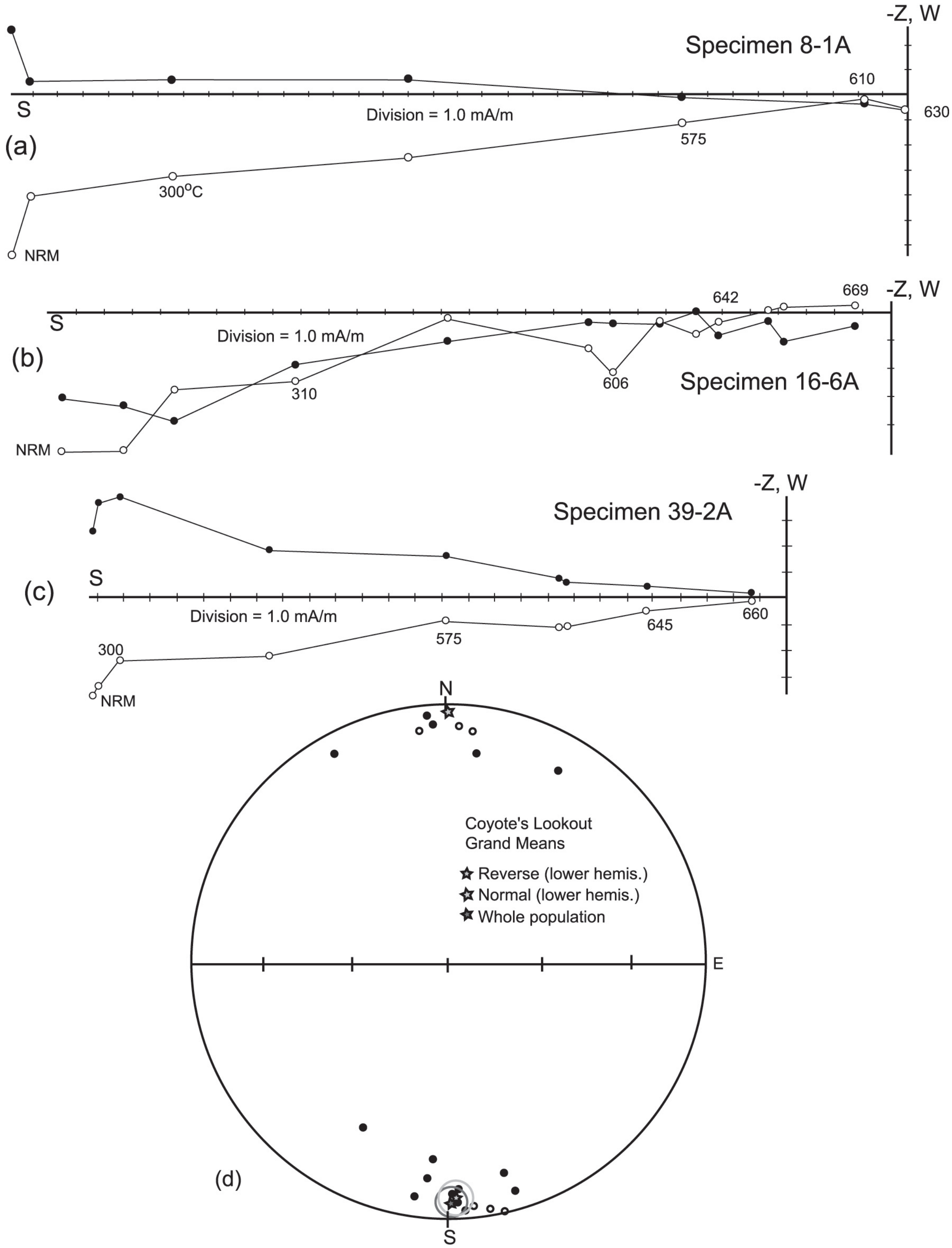


FIGURE 6. (a-c) Examples of response to progressive thermal demagnetization, specimens from samples of Painted Desert Member (Petrified Forest Formation) strata at Coyote Amphitheater. Orthogonal demagnetization diagrams (Zijderveld, 1967) showing the simultaneous projection of the horizontal (N-S vs. E-W) component of the magnetization (filled symbols) and the vertical (N-S vs. -z,+z) component of the magnetization (open symbols). For thermal demagnetization, peak demagnetizing temperatures are given beside vertical projection data. (d) Equal area projection showing site mean and grand mean direction for accepted sites from Painted Desert. strata. Closed (open) symbols refer to lower (upper) hemisphere projections.

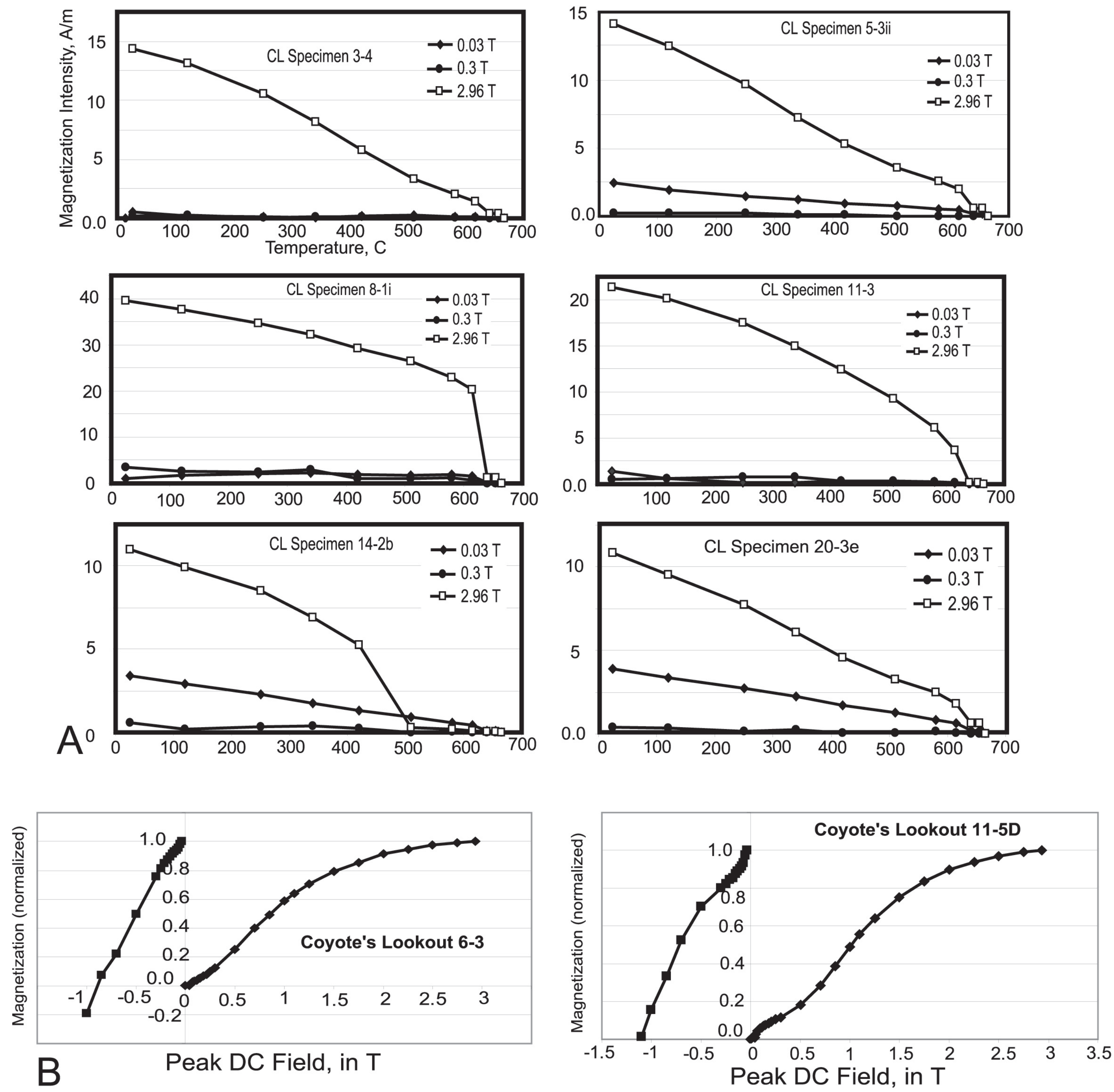


FIGURE 7. A, Plots showing the thermal demagnetization response of Painted Desert Member samples (Coyote Amphitheater) to IRM acquired along three different axes in progressive thermal demagnetization. B, IRM saturation or backfield demagnetization curves for two specimens from the Painted Desert Member.

tion and the overlying Blue Mesa Member (lower Petrified Forest Formation). The tuffaceous sandstone at the contact has yielded abundant zircons, which are currently being analyzed for a U-Pb age determination. With an internally consistent age determination from multiple zircons for this horizon, we can potentially correlate the Six Mile Canyon section with similar sections in the Chama basin and should thus be able to utilize high precision isotopic age data from the Zuni Mountains for an improved definition of the Late Triassic magnetostratigraphy of the American Southwest.

The preliminary results from the Chama basin can be compared at a gross scale with Late Triassic polarity chronologies from other localities around the world. A section of upper Chinle strata sampled at Petrified Forest National Park in eastern Ari-

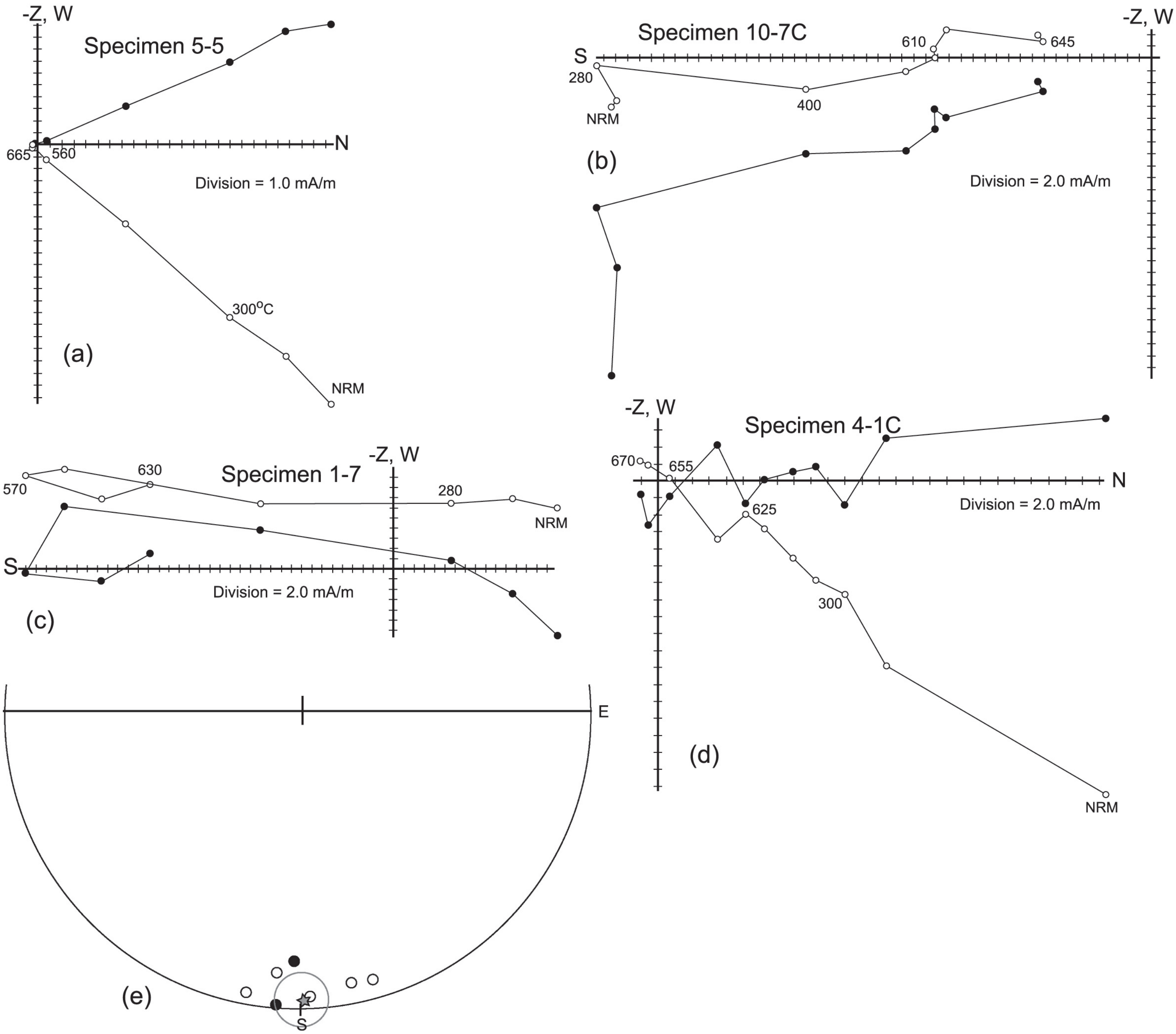


FIGURE 8. (a-d) Examples of response to progressive thermal demagnetization, specimens from samples of Bluewater Creek Formation and Blue Mesa Member strata from Six Mile Canyon. Orthogonal demagnetization diagrams (Zijgerveld, 1967) showing the simultaneous projection of the horizontal (N-S vs. E-W) component of the magnetization (filled symbols) and the vertical (N-S vs. Up-Dn) component of the magnetization (open symbols). For thermal demagnetization, peak demagnetizing temperatures are given beside vertical projection data. (e) Equal area projection showing site mean and grand mean direction for accepted sites from Bluewater Creek Formation and Blue Mesa Member strata. Closed (open) symbols refer to lower (upper) hemisphere projections.

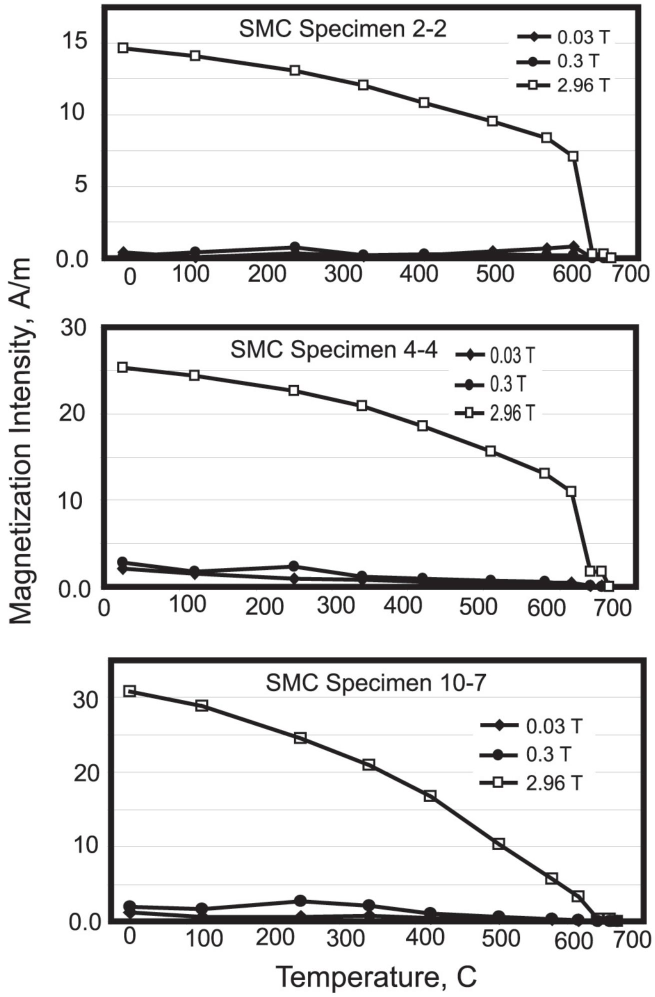


FIGURE 9. Plots showing the thermal demagnetization response of Bluewater Creek Formation and Blue Mesa Member samples (Six Mile Canyon) to IRM acquired along three different axes in progressive thermal demagnetization.

zona (Steiner and Lucas, 2000) shows the lower third of the Painted Desert Member of the Petrified Forest Formation to be dominated by reverse polarity and the upper two thirds as dominantly normal polarity. Notably, the Sonsela Sandstone, which is thought to be stratigraphically equivalent to the Poleo Formation, is reported by Steiner and Lucas (2000) to be entirely of normal polarity. The Painted Desert section sampled at Coyote Amphitheater shows a similar general pattern where the lower part is dominated by reverse polarity and the upper by normal polarity. However, all accepted site mean data from the Poleo Formation at Abiquiu Dam are almost exclusively of reverse polarity. One narrow, ill-defined short normal polarity interval exists low in the section. These results clearly differ from Steiner and Lucas' (2000) results for the Sonsela Sandstone. One possible explanation is that the interval of time over which each section has been deposited is so brief that, from the standpoint of stratigraphic correlation, the Sonsela Sandstone and the Poleo Formation are still time-equivalent. Alternatively, one of the sections has been completely remagnetized, or they are not, in fact, time equivalent.

Comparing Chama Basin data with the astronomically tuned polarity time scale for the Late Triassic based on data from the Newark Supergroup on the eastern coast of North America (Lucas and Huber, 1993; Witte and Kent, 1989; Olsen and Kent, 1999; Olsen et al., 1996, 2002 and references therein), the (Norian) Painted Desert Member section at Coyote Amphitheater shows some general similarities with the Norian part of the Newark Supergroup (Fig. 11). The lower half of the Norian in the Newark Supergroup is dominantly of reverse polarity, while the upper half is mixed with a bias towards normal polarity. Although its polarity stratigraphy has only been crudely defined to date, the lower part of the Painted Desert Member is also dominated by reverse polarity. The upper Carnian section of the Newark Supergroup is characterized by short polarity intervals, which lends support to our hypothesis that the $53^+$ m thick Poleo Formation sampled at Abiquiu Dam was deposited relatively rapidly and recorded only a single reversed polarity chron within the late Carnian.

A key goal of numerous stratigraphic investigations of the Late Triassic is to provide more robust correlations between nonmarine and marine Late Triassic records, throughout the world. Polarity information has been obtained from several carbonate-dominated Tethyan realm sections sampled in southern Europe and these also provide a basis for comparison with the the Chinle Group of northern New Mexico. These include: the Silická Brezová section in Slovakia (Channell et al., 2003), a Tethyan composite section (Krystyn et al., 2002) and a revised Pizzo Mondello section in Italy (Muttoni et al., 2004). In the Silická Brezová section, only the Carnian and Early Norian are represented (Fig. 11A). The Carnian is predominantly of normal polarity and the Early Norian is characterized by mixed polarity, but shows a bias towards reverse polarity. The Early Norian section at Silická Brezová is similar to the lower half of the Norian Painted Desert Member at Coyote Amphitheater. Once again, although the Carnian Poleo Formation at Abiquiu Dam is dominantly of reversed polarity, the presence of only a single polarity can be explained by a locally high sedimentation rate.

The Tethyan composite section (Fig. 11B) and the revised Pizzo Mondello section from Italy yield similar, mixed polarity results for the Norian. The Carnian in both of these sections is also characterized by mixed polarity. It is anticipated that further subsampling of the Chinle Group in northern and central New Mexico will yield a more robust, complete magnetostratigraphic record for much of the Late Triassic that is more similar to these two sections in terms of the number /frequency of reversals than to the polarity chronologies of the Newark Supergroup and Silická Brezová sections. We interpret the dominant reversed polarity for the Poleo Formation to indicate that sedimentation was locally rapid and quasi-continuous, as we have not identified any bonafide polarity changes at bedding plane boundaries within the Poleo Formation. There is only one, poorly defined, normal polarity interval low in the section. Based on biostratigraphy of the units that bound the Poleo Formation, this unit is most likely early Norian in age.

The current sampling interval for the mudstone-dominated Painted Desert Member is probably too coarse to allow time resolution of continuous deposition. Notably, the presence of sites

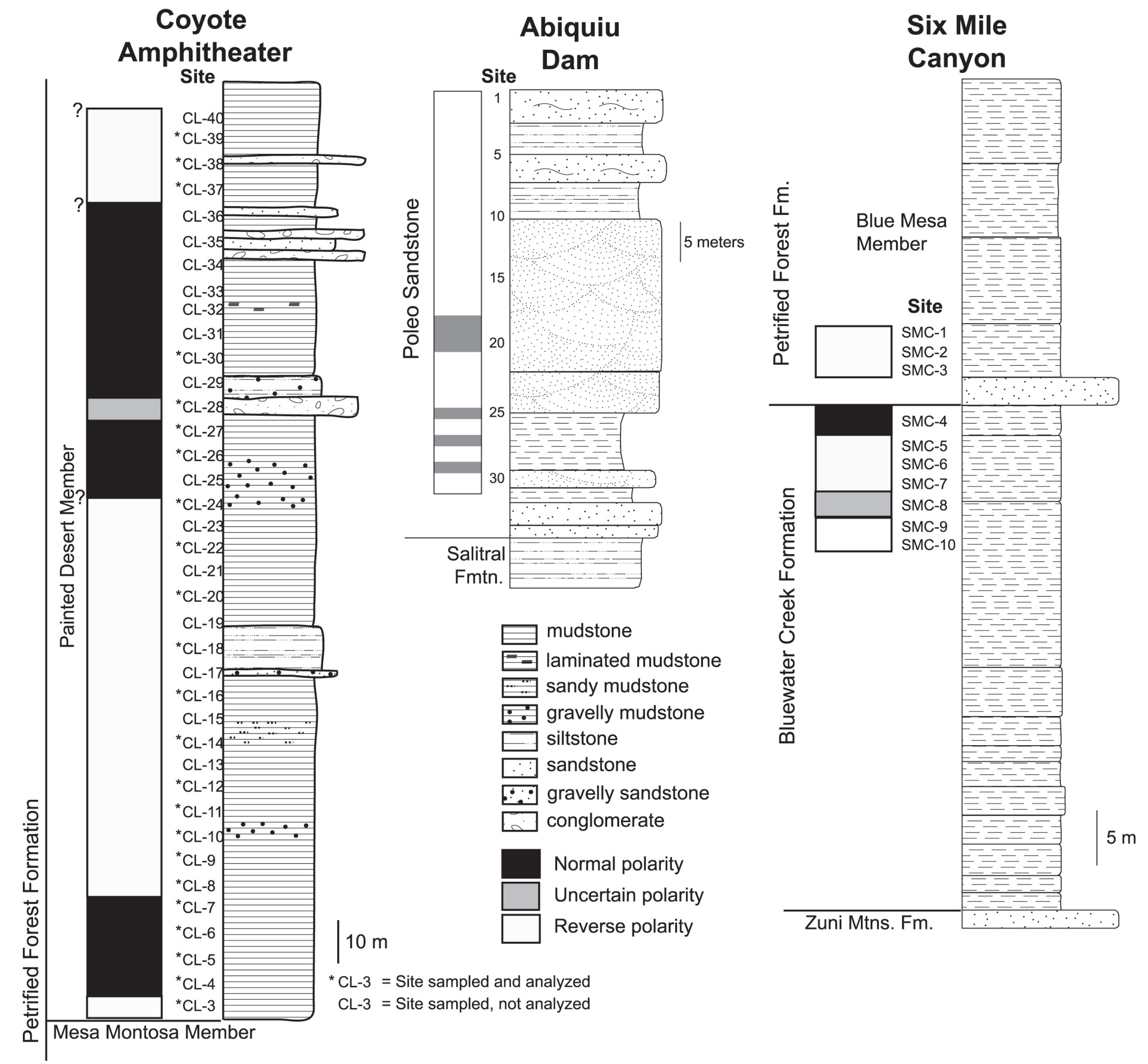


FIGURE 10. Prelimary polarity reversal zonations for the Painted Desert Member of the Petrified Forest Formation at Coyote Amphitheater (Chama Basin), the Poleo Formation at Abiquiu Dam (Chama Basin) and the Bluewater Creek Formation and Blue Mesa Member (Petrified Forest Formation) at Six Mile Canyon (Zuni Mountains).

(stratigraphic levels) that yield either uninterpretable results or demonstrate the presence of dual polarity magnetizations suggests brief hiatuses in deposition during which paleosol development began. Paleosols have been recognized by many authors as common components of Chinle Group strata (Dubiel, 1987; Dubiel et al., 1991; Parrish, 1993; Mack et al., 1993; Therrien and Fastovsky, 2000; Tanner, 2003 and references therein). An extreme example of this pedogenic modification was recognized in samples taken from the Rock Point Formation, above the *Coelophysis* quarry, near Ghost Ranch, northern New Mexico. In preliminary work on this section, specimens analyzed from four sites all yielded uninterpretable results, and the specimens showed pervasive small to medium-scale green mottling.

## CONCLUSIONS

In the Chama basin of north-central New Mexico, excellent exposures of Chinle Group strata provide a means to develop a magnetic polarity chronology for the Late Triassic. Our methods have focused not only on the drillable materials (e.g. sandstone

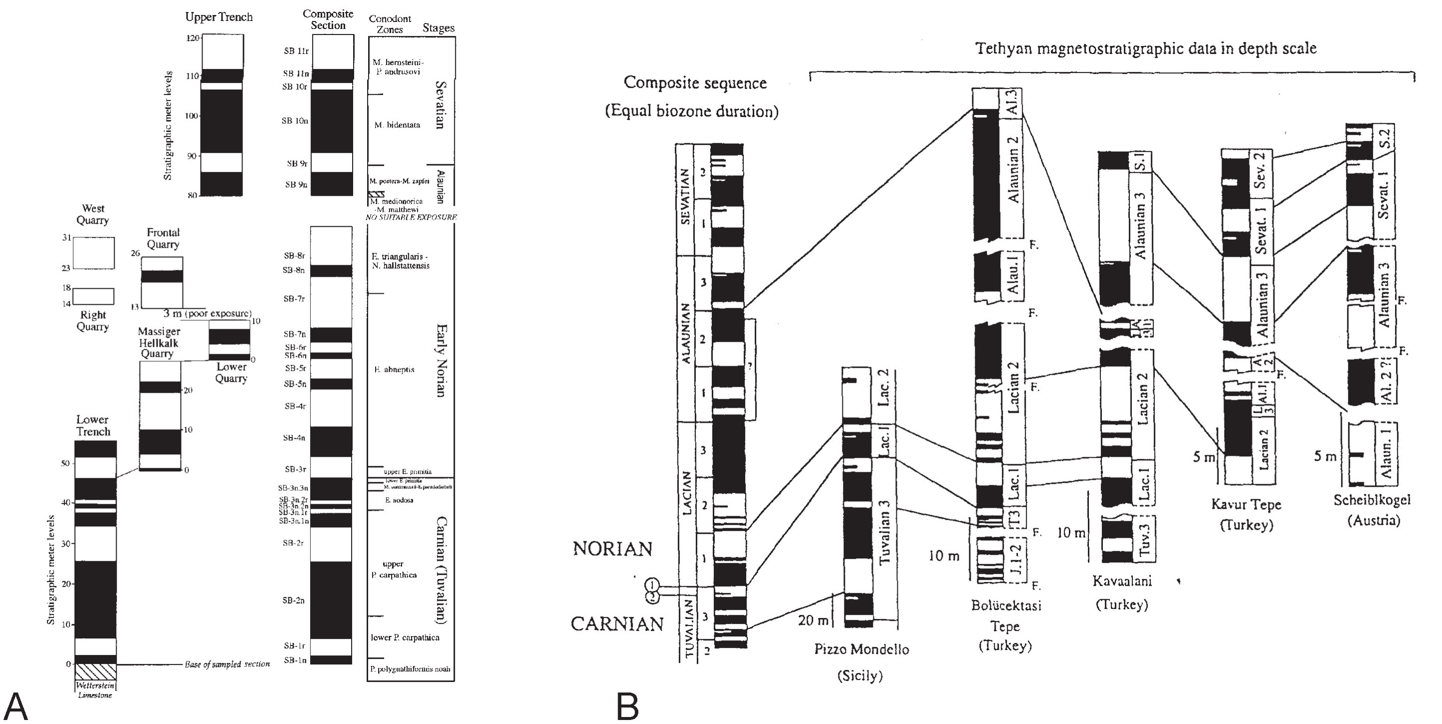


FIGURE 11. A, Magnetostratigraphy from Silická Brezová (Slovakia) (Channell et al., 2003). B, Composite Tethyan magnetostratigraphy compared to Newark Supergroup magnetostratigraphy (Krystyn et al., 2002).

and siltstone) used for previous studies (e.g., Reeve and Helsley, 1972; Reeve, 1975; Molina-Garza et al., 1996; Steiner and Lucas, 2000), but also on fine-grained rocks, primarily hematitic mudstones, which have traditionally been ignored. These fine-grained materials typically carry a well-defined and well-grouped magnetization dominated by authigenic pigmentary hematite. Coarser grained sediments contain both detrital and authigenic hematite and some magnetite; authigenic hematite is the primary magnetization carrier.

The Bluewater Creek Formation and the Blue Mesa Member (Petrified Forest Formation), sampled at Six Mile Canyon in the Zuni Mountains, are dominantly reversed polarity with a locality grand mean of D = 177.6°, I = -3.0°, $\alpha_{95}$ = 10.4° and $k$ = 34.5 (N = 7 stratigraphic levels). The Poleo Formation is of entirely reverse polarity, except for a single poorly defined normal interval low in the section, with a locality grand mean of D = 182.7°, I = -0.3°, $\alpha_{95}$ = 5.3° and $k$ = 36.5 (N = 21 sites). Its apparent lack of reversals implies that the considerable thickness of strata that accumulated at Abiquiu Dam was deposited during a brief time interval. The Petrified Forest Formation, sampled at Coyote Amphitheater, shows both normal and reverse polarity magnetizations, with preliminary results indicating a predominance of reversed polarity.

At a gross level, these initial results from the Chama basin compare reasonably well with other Late Triassic magnetostratigraphic records from Arizona, the northeast coast of North America and the Tethyan region of southern Europe. The Norian Stage was characterized by mixed polarity signal with the early Norian dominated by reverse polarity and the late Norian characterized by a mixed polarity signal. If the Poleo Formation was deposited relatively rapidly, then we have captured only a single interval of reverse polarity.

With additional sampling at these three localities and others, we will continue to refine the magnetic reversal chronology for the Late Triassic Chinle Group with the goal of developing a complete and continuous magnetostratigraphic record that can be used to test the stratigraphic completeness of the Chinle Group, as well as test future correlations and comparisons within the Chinle Group in the western United States.

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APPENDIX: Site: an individual, discrete bed or, in the case of essentially continuous mudrock intervals, an interval less than 0.5 meters thick, from which numerous, independently oriented samples were collected; Site Decl.: declination of the estimated mean magnetization direction, in stratigraphic coordinates, for the site, measured + clockwise from North; Site Incl.: inclination of the estimated mean magnetization direction, + downwards and – upwards, measured from the horizontal; Site $\alpha_{95}$: estimate of the semi-angle of the cone of confidence about which the true mean direction lies at a 95 percent confidence limit; Site *k*: estimate of the precision parameter of the distribution (Fisher, 1953); N: number of independent samples from which an accepted magnetization direction was obtained for statistical purposes; No: total number of independent samples measured.

**Six Mile Canyon (horizontal beds)**

**Blue Mesa Member, Petrified Forest Formation (Site 1 at *top* of section, section start: 12S 0728537E, 3924614N).**

| Site ID | Site Decl. | Site Incl. | Site $\alpha_{95}$ | Site *k* | N/No | Comments |
|---|---|---|---|---|---|---|
| 1 | 183.4 | -13.1 | 13.4 | 12.6 | 11/11 | |
| 2 | 189.4 | -5.0 | 10 | 37.3 | 7/7 | |
| 3 | 183.5 | 0.8 | 6.0 | 166.2 | 5/5 | less than 0.5 m above white, tuffaceous sandstone. |

**Bluewater Creek Formation (horizontal beds)**

| Site ID | Site Decl. | Site Incl. | Site $\alpha_{95}$ | Site *k* | N/No | Comments |
|---|---|---|---|---|---|---|
| 4 | NA | NA | NA | NA | 0/13 | Dual polarity results due to intense pedogenic modification of mudstone. Directly below white sandstone. |
| 5 | 167.1 | -8.7 | 22.6 | 12.5 | 5/8 | |
| 6 | NA | NA | NA | NA | 0/1 | Only a single specimen was run. |
| 7 | 187.6 | 17.5 | 10.1 | 44.6 | 6/6 | |
| 8 | NA | NA | NA | NA | 0/10 | Dual polarity results due to pedogenic modification of mudstone. |
| 9 | 176.6 | -4.5 | 10.7 | 32.7 | 7/7 | |
| 10 | 162.4 | -7.3 | 13.4 | 26.1 | 6/17 | Site mean does note include 10 specimens out of 16 run, due to pedogenic mottling that resulted in uninterpretable analyses. |
| **Grand Mean** | **Mean Decl.** | **Mean Incl.** | $\alpha_{95}$ | ***k*** | **N/No** | **Comments** |
| *in situ* | 177.6 | -3.0 | 10.4 | 34.5 | 7/10 | Paleomagnetic Pole: 56.0ºN, 75.8ºE |

**Abiquiu Dam, Poleo Formation (Site 1 is at *top* of section, section start: 13S 0371994E, 4010847N). (horizontal beds)**

| Site ID | Site Decl. | Site Incl. | Site $\alpha_{95}$ | Site *k* | N/No | Comments |
|---|---|---|---|---|---|---|
| 1 | 180.1 | -0.9 | 10.4 | 42.1 | 6/6 | |
| 2 | 193.8 | 2.6 | 6.9 | 66.0 | 8/8 | |
| 3 | 188.5 | 4.5 | 8.0 | 49.1 | 8/8 | |
| 4 | 182.3 | 7.2 | 11.1 | 30.3 | 7/8 | |
| 5 | 190.0 | 9.3 | 3.5 | 213.7 | 9/9 | |
| 6 | 186.0 | 2.3 | 2.5 | 479.5 | 8/8 | |
| 7 | 185.7 | -5.6 | 7.9 | 50.2 | 8/8 | |
| 8 | 182.3 | -11.2 | 7.0 | 76.2 | 7/7 | |
| 9 | 178.4 | 0.3 | 15.4 | 16.3 | 7/8 | |
| 10 | 179.1 | -12.2 | 19 | 13.4 | 6/8 | |
| 11 | 187.4 | 0.8 | 3.4 | 268.1 | 8/8 | |
| 12 | 169.8 | -8.2 | 9.3 | 42.8 | 7/7 | |
| 13 | 175.6 | 5.3 | 11.9 | 42.3 | 5/7 | |
| 14 | 170.9 | 6.4 | 4.1 | 216.5 | 7/7 | |
| 15 | 167.7 | 9.2 | 5.3 | 96.8 | 9/9 | |
| 16 | 168.7 | 8.9 | 6.6 | 70.6 | 8/8 | |
| 17 | 8.1 | 84 | 66.3 | 1.8 | 7/8 | Rejected, high dispersion. |
| 18 | 134 | -71.5 | -59.3 | 1.2 | 7/8 | Rejected, high dispersion. |
| 19 | 205.8 | -4.2 | 15.1 | 16.8 | 7/8 | |
| 20 | NA | NA | NA | NA | 0/6 | Uninterpretable results. |
| 21 | 198.7 | 5.3 | 75 | 2.5 | 3/7 | Rejected, high dispersion. |
| 22 | 181.4 | -12.1 | 6.1 | 99 | 7/7 | |
| 23 | 177.2 | 4.1 | 13.6 | 25.2 | 6/6 | |
| 24 | 187.2 | -7.3 | 27.5 | 21.2 | 3/7 | Rejected, high dispersion. |
| 25 | NA | NA | NA | NA | 0/8 | Conglomerate, results uninterpretable. |
| 26 | 180 | -6.4 | 20.8 | 7.1 | 9/9 | |
| 27 | 45.8 | -30.6 | 76.3 | 2.4 | 4/7 | Rejected, high dispersion. |

APPENDIX - cont.

| | | | | | | |
|---|---|---|---|---|---|---|
| 28 | 165.6 | -3.2 | 86.8 | 1.7 | 5/9 | Rejected, high dispersion. |
| 29 | 211.3 | -26.9 | 45.1 | 2.5 | 9/9 | Rejected, high dispersion. |
| 30 | 207.6 | -15.1 | 10.8 | 23.6 | 9/9 | |

| **Grand Mean** | **Mean Decl.** | **Mean Incl.** | $\alpha_{95}$ | ***k*** | **N/No** | **Comments** |
|---|---|---|---|---|---|---|
| *in situ* | 182.7 | -0.3 | 5.3 | 36.5 | 21/30 | Paleomagnetic Pole: 53.9ºN, 69.2ºE |

Coyote Amphitheater Section, Painted Desert Member, Petrified Forest Formation (Site 1 is at the bottom of section, section start: 13S 0353448E, 4009282N). (Only sites prepared and measured are listed)

| **Site ID** | **Site Decl.** | **Site Incl.** | **Site $\alpha_{95}$** | **Site *k*** | **N/No** | **Comments** |
|---|---|---|---|---|---|---|
| 3 | 169.0 | -3.5 | 9.7 | 163.6 | 3/16 | |
| 4 | 002.2 | -10.4 | 19.7 | 16.1 | 5/5 | |
| 5 | 353.9 | 3.9 | 10.5 | 10.1 | 21/32 | |
| 6 | 028.4 | 15.6 | 40.7 | 39.8 | 2/2 | Rejected, high dispersion. |
| 7 | 354.9 | 8.0 | 14.9 | 7.1 | 16/26 | |
| 8 | 173.1 | -6.3 | 10.9 | 38.9 | 6/6 | |
| 9 | 177.7 | 13.8 | 9.0 | 188.6 | 3/3 | |
| 10 | 186.8 | 8.9 | 20.3 | 21.5 | 4/5 | |
| 11 | NA | NA | NA | NA | 0/11 | Dual polarity results. |
| 12 | 175.3 | 8.9 | 10.1 | 58.3 | 5/6 | |
| 14 | 206.9 | 28.4 | 17.7 | 19.6 | 5/5 | |
| 16 | 183.3 | 24.5 | 8.4 | 30.5 | 11/13 | |
| 18 | 166.7 | -0.6 | 10.0 | 46.1 | 6/7 | |
| 20 | 184.1 | 17.3 | 14.5 | 15.6 | 8/10 | |
| 22 | 164.0 | 16.4 | 31.3 | 16.6 | 3/3 | Rejected, high dispersion. |
| 24 | 178.7 | 10.8 | 15.9 | 24.1 | 5/7 | |
| 26 | 328.8 | 8.8 | 36.7 | 5.3 | 5/7 | Rejected, high dispersion. |
| 27 | 351.9 | -11.8 | 14.1 | 19.2 | 7/7 | |
| 28 | 006.6 | 19.7 | 51.3 | 25.9 | 2/3 | Rejected, high dispersion. |
| 30 | 001.1 | -9.4 | 13.6 | 32.5 | 5/5 | |
| 37 | 163.4 | 8.2 | 2.7 | 1132.6 | 4/4 | |
| 38 | 177.4 | 7.7 | 39.5 | 42.1 | 2/2 | Rejected, high dispersion. |
| 39 | 172.9 | 7.0 | 5.5 | 102.5 | 8/8 | |

| **Grand Mean** | **Mean Decl.** | **Mean Incl.** | $\alpha_{95}$ | ***k*** | **N/No** | **Comments** |
|---|---|---|---|---|---|---|
| *in situ corrected* 354/18W | 179.5 | 6.1 | 6.3 | 23.5 | 17/23 | Paleomagnetic Pole: 57.0ºN, 74.5ºW |

# PLATE 2: GENERALIZED GEOLOGIC MAP – NORTH-CENTRAL NEW MEXICO


PLATE 2. Geologic map and block diagrams of north-central New Mexico. The geologic map is based largely on 1:500,000 geologic maps of New Mexico and Colorado (NMBGMR, 2004; Tweto, 1979).

# PLATE 3 - AEROMAGNETIC MAP OF NORTH-CENTRAL NEW MEXICO

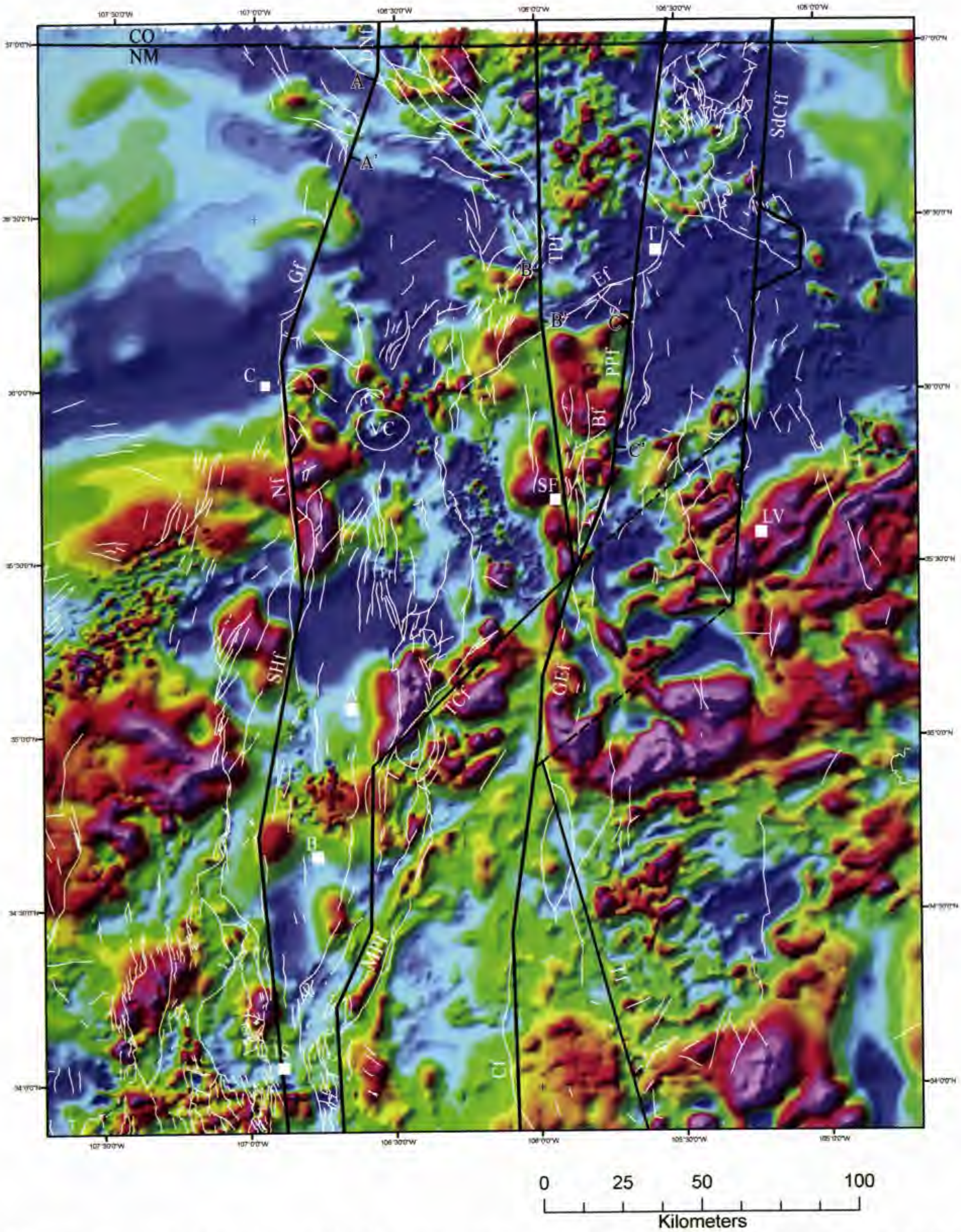


PLATE 3. Aeromagnetic map of part of north-central New Mexico (from Kucks et al. 2001). Heavy line at top is the Colorado–New Mexico state line. Faults (white lines) are from the New Mexico Bureau of Geology and Mineral Resources (2003). Heavy lines are cut lines used in this reconstruction; note that heavy dashed lines southwest of Las Vegas are cut lines that represent ficticious faults used to approximate the southward plunge-out of the Sangre de Cristo uplift (Plate 2). Reference points are: C, Cuba; A, Albuquerque; SF, Santa Fe; VC, Valles caldera; T, Taos; LV, Las Vegas; S, Socorro; B, Belen. Selected geologic structures are: DNf, Del Norte fault (not exposed); GF, Gallina fault; Nf, Nacimiento fault; SHf, San Hill fault; MPf, Montosa–Palomas–Hubble Springs faults; TCf, Tijeras–Cañoncito fault; Ef, Embudo fault; TPf, Tusas–Picuris fault (not exposed); Bf, Borrego fault; PPf, Picuris–Pecos fault; GEf, Glorieta Mesa–Estancia Basin fault; Cf, Chupadera fault; SdCff, Sangre de Cristo frontal faults. A–A´, B–B´, and C–C´ are match points used to reconstruct dextral separations in Plate 2.

# PLATE 4: DISTRIBUTION OF CONTRACTION AND EXTENSION FOR PHANEROZIC TECTONIC EVENTS IN NORTHERN NEW MEXICO