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MAGNETOSTRATIGRAPHY OF THE UPPER TRIASSIC CHINLE GROUP IN NEW MEXICO: AN APPRAISAL OF 40 YEARS OF ANALYSIS

SPENCER G. LUCAS AND JUSTIN A. SPIELMANN

New Mexico Museum of Natural History and Science, 1801 Mountain Rd. NW, Albuquerque, NM 87104-1375

Abstract—In New Mexico (NM), Upper Triassic strata of the Chinle Group are nonmarine siliciclastic red beds containing an an extensive fossil record that demonstrates a late Carnian to early Rhaetian age, about 230-203 Ma. Magnetostratigraphic studies of the Chinle Group in NM began in the 1970s and have produced complete Chinle magnetostratigraphies in east-central NM (Tucumcari basin) and north-central NM (Chama basin), and partial Chinle magnetostratigraphy in some other parts of the state. However, despite the number of studies, the resultant magnetostratigraphic data are generally of low reliability and do not allow unambiguous correlations based on pattern matching, even within the Chinle outcrop belt in NM. Particularly problematic is recently published Chinle magnetostratigraphy in the Chama basin in which the sampling interval is inadequate and poorly constrained (2-5 meters), some lithostratigraphic correlations are demonstrably incorrect and biostratigraphic datum points are ignored. If we correlate the NM Chinle Group using established lithostratigraphy and biostratigraphy, the magnetostratigraphic data do indicate that the late Carnian is a normal multichron, the early-middle Norian is of mixed polarity and the late Norian is a normal multichron, which is consistent with the global pattern. Although Chinle magnetostratigraphy has been conducted in NM for over 40 years by various laboratories and researchers, the results provide few or no correlations locally or regionally that improve those achieved by lithostratigraphy and biostratigraphy. Chinle Group magnetostratigraphy in NM has also made little contribution to development of a global polarity timescale for Triassic time. Very variable sedimentation rates and numerous depositional hiatuses make the Chinle Group a poor prospect for magnetostratigraphic analysis.

INTRODUCTION

Magnetostratigraphy can provide a powerful tool for correlation in concert with biostratigraphic and/or radioisotopic-age data. This is certainly the case for much of Cretaceous and all of Cenozoic time for which an agreed on global polarity timescale (GPTS) exists to which local magnetostratigraphic results can be correlated. The GPTS extends back to the Middle Jurassic, but there is no agreed on GPTS for the Triassic.

In order to create a Triassic GPTS diverse magnetostratigraphic sections from both marine and nonmarine Triassic strata have been correlated to assemble an apparently complete record of Triassic polarity history (see Hounslow and Muttoni, 2010, for the most recent attempt). Among the polarity records available are those from the nonmarine Upper Triassic Chinle Group in New Mexico (Fig. 1). Study of Chinle Group magnetostratigraphy began in New Mexico during the early 1970s. Here, we review those studies and their results to evaluate critically the utility of Chinle Group magnetostratigraphy in correlation and in construction of a Triassic GPTS.

CHINLE GROUP

The Chinle Group (Lucas, 1993) encompasses Upper Triassic nonmarine strata exposed in the western USA over an area of at least 2.3 million km^2 that extends from Texas to Wyoming and from Oklahoma to Nevada. The group includes at least 50 named lithostratigraphic units (formations, members and beds) that in the older literature were generally considered members of the Chinle Formation (especially in Arizona, Utah and New Mexico) or Dockum Formation (especially in Texas). Elevation of the Chinle Group thus unified a once parochial lithostratigraphic nomenclature and now refers to the single lithosome that was deposited across the vast Chinle basin during Late Triassic time (e.g., Lucas, 1993, 1997; Lucas and Huber, 1994; Lawton, 1994; Dickinson and Gehrels, 2008).

Maximum Chinle Group thickness is about 500 m (in eastern New Mexico: Lucas et al., 2001), but typical regional thicknesses are

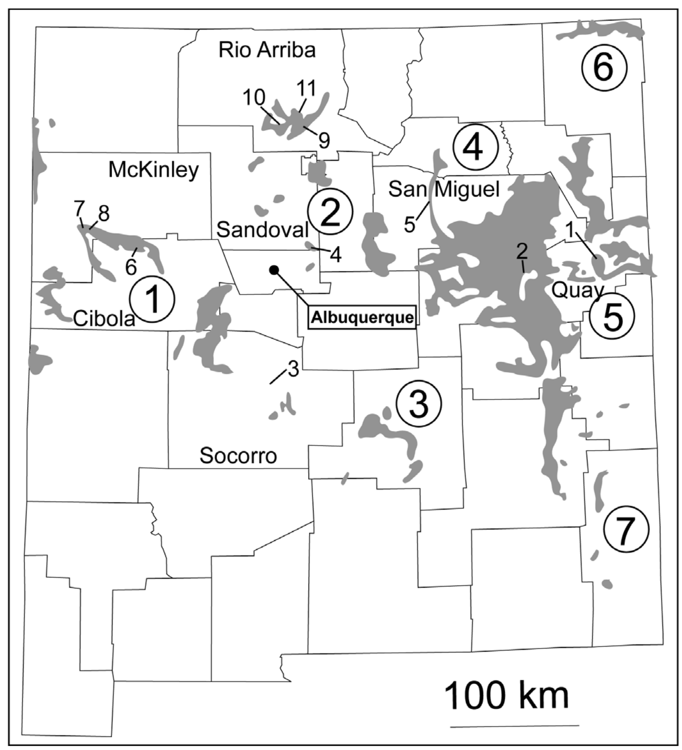

FIGURE 1. Map of Chinle Group outcrop pattern in New Mexico showing locations of magnetic polarity sections shown in Figures 3 and 4 (small numbers) and location of stratigraphic columns in Figure 2 (large numbers in circles). Magnetic polarity sections are: **1**, Mesa Redonda; **2**, Montoya Point; **3**, Sevilleta Grant; **4**, Hagan basin; **5**, Sangre de Cristo Mountains (Montezuma Gap and Sebastian Canyon); **6**, Bluewater Creek; **7**, Fort Wingate; **8**, Sixmile Canyon; **9**, Abiquiu Dam; **10**, Coyote Amphitheater; **11**, Ghost Ranch.

about 200-300 m. Chinle Group strata are mostly red beds, though some portions (particularly in the lower part of the group) are variegated blue, purple, olive, yellow and gray. Sandstones are mostly fluvial-channel deposits that range from mature quartzarenites to very immature litharenites and graywackes. Conglomerate clasts are extrabasinal (silica pebbles derived from mature basement or Paleozoic limestone pebbles) or intrabasinal (mostly nodular calcrete rip-ups) or a mixture of both. Most mudstones are bentonitic, except in the youngest Chinle strata, and typically are pedogenically modified floodplain deposits (e.g., Tanner and Lucas, 2006). Local and regional lacustrine deposits encompass analcimolite and pisolitic limestone (e.g., Tanner and Lucas, 2012). Within this array of lithotypes, red coloration, overall sandstone immaturity and textures and sedimentary structures characteristic of fluvial deposition and a general abundance of volcanic detritus lend Chinle Group stratigraphic units lithologic characters that facilitates their ready identification and correlation.

Lucas (1993; also see Lucas and Huber, 1994, 2003) presented a correlation of Chinle Group lithostratigraphic units based on lithostratigraphy supported primarily by vertebrate biostratigraphy (Lucas and Hunt, 1993; Lucas, 1997, 1998, 2010; Lucas et al., 2007). This lithostratigraphic correlation reflects the relatively consistent stratigraphic architecture of the Chinle Group across most of its depositional extent. In New Mexico this correlation (Fig. 2) is well established by lithostratigraphic and biostratigraphic data (Lucas, 2004).

This lithostratigraphic/biostratigraphic framework allows confident placement of the Chinle Group magnetostratigraphic sections into stratigraphic order. From this stratigraphic ordering, achieved by using datasets (lithostratigraphy and vertebrate biostratigraphy) independent of magnetostratigraphy, it is possible to evaluate the utility of magnetostratigraphic correlations in the Chinle Group.

HISTORY

We list and briefly summarize magnetostratigraphic studies of Chinle Group strata in New Mexico. Note, though, that these studies represent most of the magnetostratigraphy done in the Chinle Group; studies of Chinle magnetostratigraphy outside New Mexico, in Arizona and Utah, are very few (e.g., Steiner and Lucas, 2000; Molina-Garza et al., 2003).

1. Reeve and Helsley (1972) published the first study of Chinle Group magnetostratigraphy in New Mexico. Thus, they established the magnetic polarity of two stratigraphic sections of the upper part of the Bull Canyon Formation and all of the overlying Redonda Formation in Quay County (Fig. 1). In a sense, their work followed that of Graham (1955) and Cox and Doell (1960), who had obtained paleopoles, but not magnetic polarity data from the Redonda strata. Reeve and Helsley obtained mostly reversed polarity from these strata except in the upper 30-40 m of the Redonda Formation, which yielded mostly normal polarity (Fig. 3). Reeve (1975), in his unpublished Ph.D. dissertation, reiterated the results of Reeve and Helsley (1972).

Significantly, despite the relative antiquity of Reeve's and Helsley's (1972) work, nobody has completely replicated (or at least redone) their work. Bazard and Butler (1989, 1991) published paleopole data based on Redonda samples but not a magnetic polarity stratigraphy. Zeigler and Geissman (2012, fig. 12) published a very incomplete magnetic

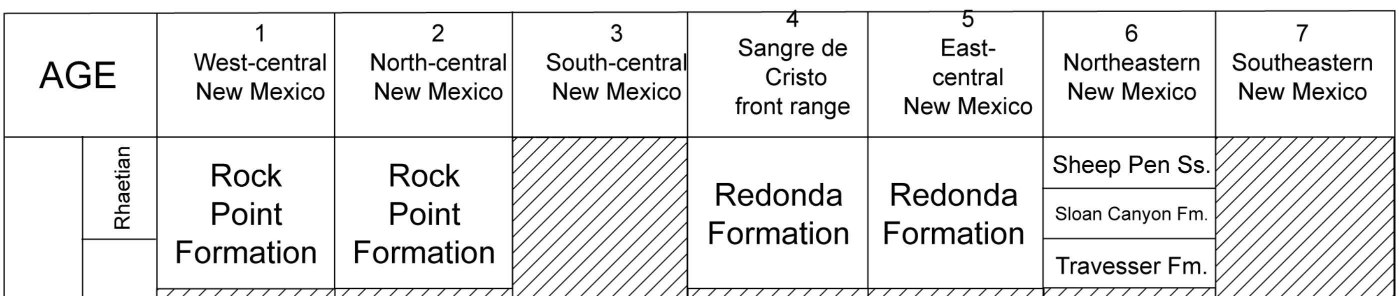

FIGURE 2. Correlation of Chinle Group strata in New Mexico based on lithostratigraphy and biostratigraphy (from Lucas, 2004). See Figure 1 for location of columns.

polarity record (much of it of uninterpretable polarity) of the Redonda Formation at Mesa Redonda based on sampling undertaken during the last decade (see below). Thus, Reeve's and Helsley's (1972) upper Chinle magnetostratigraphy continues to appear in articles decades later (such as Hounslow and Muttoni, 2010) and has never been replicated.

2. As already noted, Bazard and Butler (1989, 1991) published paleopole data from the Redonda Formation. In his unpublished Ph.D. dissertation, Bazard (1991) did develop a Redonda Formation magnetostratigraphy, but he never published it.

3. Molina-Garza et al. (1991, 1993) published magnetostratigraphic data from the Chinle Group in the Sangre de Cristo Mountains of San Miguel County, at Bluewater Creek in the Zuni Mountains of Cibola County, on the Sevilleta Grant in Socorro County and in the Hagan basin of Sandoval County (Figs. 1, 3). Molina-Garza et al. (1996, 1998) later published additional data on some of these sections, and for other sections very close to them. From these data, and those of Reeve and Helsely (1972), Molina-Garza et al. (1993) constructed a composite Chinle Group magnetostratigraphy (Fig. 3).

4. Zeigler (2008) undertook a Ph.D. dissertation on Chinle Group magnetostratigraphy in the Chama basin of northern New Mexico (Fig. 1). Results of this work, as well as a section studied in part of the lower Chinle Group in the Zuni Mountains (Six Mile Canyon: Figs. 1, 4), were published by Zeigler et al. (2005, 2008) and by Zeigler and Geissman (2012). In what we regard as a summary result of this work, Zeigler and Geissman (2012, fig. 12) correlated most of the Chinle Group magnetostratigraphic sections in New Mexico to those available in Arizona and Utah to develop a composite Chinle Group magnetostratigraphy (Fig. 4).

EVALUATION

The stated goal of this article is to present a critical evaluation of Chinle Group magnetostratigraphy in New Mexico. Such an evaluation is based on two questions: (1) how well can Chinle strata be correlated to each other using magnetostratigraphy?; and (2) does Chinle Group magnetostratigraphy match or contribute to the currently understood Late Triassic GPTS?

Correlations Within the Chinle Group

A comparison of the composite Chinle magnetostratigraphy of Molina-Garza et al. (1993) and of Zeigler and Geissman (2012) reveals little correspondence (compare Figures 3 and 4). In part, this reflects the different datasets used by these two groups. Thus, Molina-Garza et al. (1993) obviously did not have access to the magnetostratigraphic data later collected by Zeigler (2008), and only used data from New Mexico. However, Zeigler and Geissman (2012) chose not to include some of the

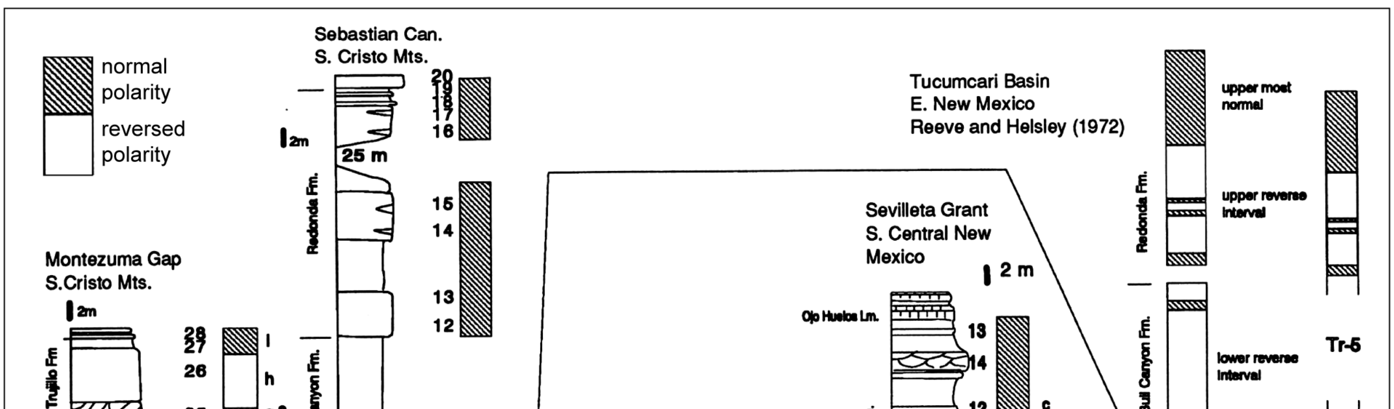

FIGURE 3. Summary of Chinle Group magnetostratigraphy undertaken in New Mexico through the early 1990s (after Molina-Garza et al., 1993). See Figure 1 for location of columns. Column on far right is composite Chinle Group magnetostratigraphy. Tr-4 and Tr-5 are regional, within-Chinle unconformities (Lucas, 1993).

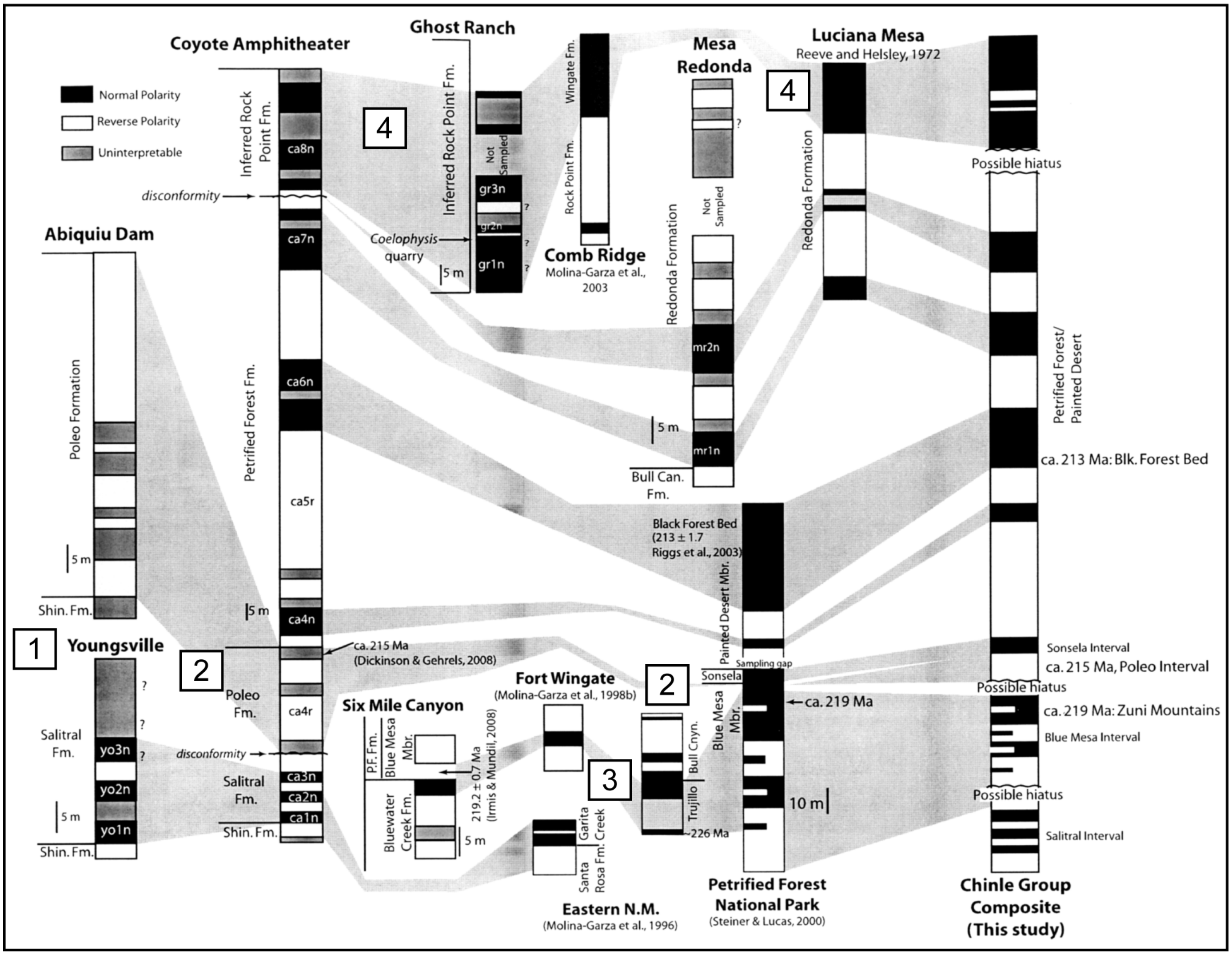

FIGURE 4. Correlation of Chinle Group magnetic polarity sections in New Mexico, Arizona and Utah, and a composite magnetic polarity stratigraphy for the Chinle Group (after Zeigler and Geissman, 2012). Numbers in boxes correspond to points of discussion in the text.

magnetostratigraphic sections from New Mexico used by Molina-Garza et al. (1993), but did add new data from Zeigler (2008), as well as data from Chinle strata in Arizona and Utah.

One obvious example of the lack of correspondence in the analyses of Molina-Garza et al. (1993) and Zeigler and Geissman (2008) is the polarity of the base of the Chinle Group. In the analyses used by Molina-Garza et al. (1993), the basal Chinle Group is of normal polarity in three sections (Fig. 3), but Zeigler and Geissman (2012) show it as of reversed polarity (Fig. 4).

Magnetostratigraphic correlation within the Chinle Group using the data available to Molina-Garza et al. (1993) is of poor resolution. For example, the Trujillo Formation in two closely spaced sections in the Sangre de Cristo Mountains has very dissimilar polarity patterns, and Chinle strata below that are a mixture of reversed and normal polarity that do not match in correlative units (upper Santa Rosa-Garita Creek correlates to Bluewater Creek Formation and lower part of San Pedro Arroyo Formation: Fig. 2). To make the composite Chinle magnetostratigraphy, Molina-Garza et al. (1993) tried to stratigraphically order the reversals, but clearly had to accept that in all sections some reversals were missing and that relative thickness of reversals (and thus the actual polarity pattern) varies greatly between sections. Furthermore, much of their composite Chinle magnetic polarity is based on single data points that are widely separated stratigraphically, especially in the upper part of the Chinle Group. And, even though their own magnetostratigraphic data in the Sangre de Cristo Mountains show the Redonda Formation to be of dominantly normal polarity, they used the 20+ year-old-study of Reeve and Helsley (1972) to override that and show a mixed polarity pattern for the Redonda Formation (Fig. 3).

Magnetostratigraphic correlations within the Chinle Group proposed by Zeigler and Geissman (2008) are more problematic because some are contradicted by well-established lithostratigraphic/biostratigraphic correlations and because of internal inconsistencies and contradictions in their work. Examples (see numbers on Figure 4) include: (1) stacking the magnetostratigraphic sections at Youngsville and Abiquiu Dam as if they are stratigraphically successive, when, in fact, they overlap (both have Shinarump Formation at their bases, and there is Salitral Formation between Shinarump and Poleo at Abiquiu Dam: Lucas and Hunt, 1992; Zeigler et al., 2005; Lucas et al., 2005); (2) correlation of Poleo Formation polarity columns between Abiquiu Dam and Coyote Amphitheater is of two mostly reversed polarity intervals with many intervals of uninterpretable polarity, which are correlated to an interval of normal polarity in the Sonsela Member of the Petrified Forest Formation in Arizona; (3) the Trujillo Formation, a correlative of the Poleo and Sonsela, in eastern New Mexico, and the overlying Bull Canyon Formation, are both correlated to strata older than the Sonsela Member, which contradicts lithostratigraphic and biostratigraphic correlations; and (4) the Rock Point Formation in the Chama basin sections, the correlative of the Redonda Formation, is of dominantly normal polarity and only correlated to the upper part of the Redonda Formation using Reeve and Helsley's 40-year-old Redonda magnetic polarity record. These and other issues make it difficult to accept the composite Chinle Group magnetic polarity stratigraphy of Zeigler and Geissman (2012). Particularly problematic are their separate "Blue Mesa interval" and "Salitral interval" as these units overlap temporally (Fig. 2). Also, the youngest part of their composite polarity stratigraphy, above the stratigraphically highest "possible hiatus," bears no resemblance to the magnetic polarity columns upon which it is supposedly based.

What we can do is attempt to correlate the magnetostratigraphic data presented by Zeigler and Geissman (2012) based on lithostratigraphy/biostratigraphy to see if consistent within-Chinle Group correlations are supported by magnetostratigraphy. It is evident that, in many cases, their magnetostratigraphy does not provide this support. Thus, all strata below the Poleo-Sonsela-Trujillo are of mixed polarity (or of largely uninterpretable polarity) – Shinarump, Salitral, Bluewater Creek, Blue Mesa, Santa Rosa and Garita Creek formations/members – and we see no consistent correlation of any of these patterns to each other. The Poleo is of dominantly reversed polarity (and much uninterpretable polarity), but its correlatives the Trujillo and Sonsela are of normal polarity. Magnetostratigraphic correlation within the Painted Desert interval requires vast changes in sedimentation rates, and correlations within the Redonda-Rock Point interval are similar to those in the pre-Poleo interval – a complex mixture of normal, reversed and uninterpretable polarity that shows no consistent patterns from section to section.

Can we, however, arrive at some sort of composite Chinle magnetic polarity pattern using the multichron concept of Lucas (2011)? Indeed, given the current state of the Triassic GPTS, much Triassic magnetostratigraphic correlation is achieved by matching groups of closely spaced chrons (multichrons) to each other instead of by matching individual chrons (cf. Hounslow and Muttoni, 2010). Thus, we can conclude, based on all the data presented by Molina et al. (1993) and by Zeigler and Geissman (2012), that the lower Chinle Group, below the Bull Canyon/Painted Desert interval, is a multichron, of mostly normal polarity, that the overlying middle-upper Chinle Group (Painted Desert/Bull Canyon) is a mostly reversed multichron and that the Rock Point-Redonda interval is a dominantly normal multichron (Fig. 5). More detailed composite Chinle magnetostratigraphies are possible, like those shown in Figures 3 and 4, but, as discussed above, are not well supported by reliable data.

Chinle Group Magnetostratigraphy and the Triassic GPTS

Given how few reliable magnetic-polarity-based correlations can be made within the Chinle Group of New Mexico, it is difficult to arrive at a credible, detailed polarity history of the Chinle Group. Therefore, the Chinle Group magnetostratigraphy contributes little to a Triassic GPTS.

In the compilation of a Triassic GPTS by Hounslow and Muttoni (2010, fig. 11), the only Chinle Group magnetostratigraphic data from New Mexico used were from Reeve and Helsley (1972) and Molina-Garza et al. (1996). These data were regarded as of Norian-Rhaetian age and correlated to the Newark magnetostratigraphy by the questionable concept of a "long Norian." Therefore, Chinle strata of demonstrable Norian age, such as the Trujillo and Bull Canyon formations, were magnetostratigraphically correlated to Carnian strata in the Newark below the level of the E16/E17 reversal boundary, which is the biostratigraphic position of the Carnian-Norian boundary (Lucas et al., 2012). Thus, Hounslow and Muttoni's (2010) magnetostratigraphic correlation of the upper Chinle Group in New Mexico to the Newark magnetostratigraphy is contradicted by biostratigraphy. The fact that they were able to apparently pattern match Chinle magnetostratigraphy to some extent to Newark magnetostratigraphy in a biostratigraphically incorrect correlation shows how poorly constrained magnetostratigraphic patterns are in much of the Late Triassic. Indeed, if biostratigraphic data are ignored, Chinle magnetostratigraphy can be correlated in numerous ways to the Newark magnetostratigraphy (Fig. 5).

CHINLE MAGNETOSTRATIGRAPHY: QUO VADIS?

Magnetostratigraphic studies of the Chinle Group in New Mexico have failed to produce a polarity record useful to within Chinle correlation. This polarity record also (logically) contributes little to the development of a Triassic GPTS. Why?

The first answer is twofold and involves the magnetostratigraphic studies themselves. It is fair to say that too few Chinle Group magnetostratigraphic sections have been analyzed to produce a repeated, consistent polarity pattern beyond the multichrons we have identified. More studies, particularly of closely spaced sections that correlate to each other unambiguously, may produce more consistent and correlateable results.

However, the second part of this answer is the poor quality of many of the Chinle Group magnetostratigraphic data. The study of Zeigler (2008) as published by Zeigler and Geissman (2012) well exemplifies this. Thus, all of their magnetostratigraphic sections of the Chinle Group in the Chama Basin contain significant intervals of "uninterpretable" polarity (Fig. 4). The sampling interval was very wide (~3 m, in some cases as much as 5 m), and many samples (especially mudrock) did not yield a reliable polarity. Given these limitations, the ability to magnetostratigraphically correlate Chinle Group sections in the Chama basin is compromised. The fact that some of these strata have polarity apparently dissimilar to strata deemed correlative based on lithostratigraphy and biostratigraphy (example Poleo-Sonsela-Trujillo) may simply indicate that the data of Zeigler (2008) are not adequate to establish the polarity of much of the Chinle Group section in the Chama Basin.

Beyond problems inherent to the magnetostratigraphic studies, the Chinle Group arguably is a poor candidate for faithfully recording much of Late Triassic magnetic polarity history. Total Chinle thickness is a maximum of 500 m, usually much less. By any reasonable correlation, it represents much of Carnian, all of Norian and perhaps part of Rhaetian time, which is a span of at least 25 million years. If we double total Chinle thickness to 1000 m, to offset compaction, this gives an overall average sedimentation rate of the Chinle Group of only 40 mm/1000 years. This is an extremely low sedimentation rate for fluvial sediments (Sadler, 1981). However, this low rate is in part a function of how long an interval of time is being considered—in such calculations, the longer the time interval, the lower average rates of sedimentation tend to be (Sadler, 1981). What is most likely is that Chinle sedimentation rates varied widely, from short-term rapid accumulation to nondeposition and erosion.

The Chinle is an unconformity-bounded unit, and two within Chinle unconformities of regional extent have been posited (Lucas, 1993). Deposition of the Chinle was by fluvial processes, so it was evidently episodic, and many local hiatuses must be present. Thus, we expect the Chinle Group to record only fragments, "snapshots" if you will, of Late Triassic magnetic polarity history, not a complete or even nearly complete record. A sound, biostratigraphically-based correlation of the Chinle multichrons – late Carnian mostly normal, early-middle Norian mostly reversed, late Norian-Rhaetian mostly normal – fits the currently conceived Triassic GPTS, but this may be as precise a magnetostratigraphic correlation as is possible.

Another way to gauge the incompleteness of a composite Chinle magnetostratigraphy is to compare it to the coeval Newark magnetostratigraphy (Fig. 5). If we accept biostratigraphic correlations (e.g., Lucas et al., 2012), the Chinle magnetostratigraphy should correlate to all or most of Newark chrons E1 through E22. The much larger number of Newark magnetochrons for the time interval late Carnian-

Rhaetian is prima facie evidence that the Chinle magnetostratigraphy is relatively incomplete (Fig. 5).

This, of course, raises serious questions about future studies of Chinle magnetostratigraphy. We believe that such studies, which include a proposed coring of the entire Chinle Group in Arizona (Olsen et al., 2009), will recover a patchy and incomplete record of Late Triassic magnetic polarity history. This record will be difficult to impossible to correlate to the much more complete, coeval portion of the Newark magnetostratigraphy. Thus, given the nature of Chinle Group deposition, we judge it to be a poor prospect for magnetostratigraphic study that will contribute little to development of a Triassic GPTS.

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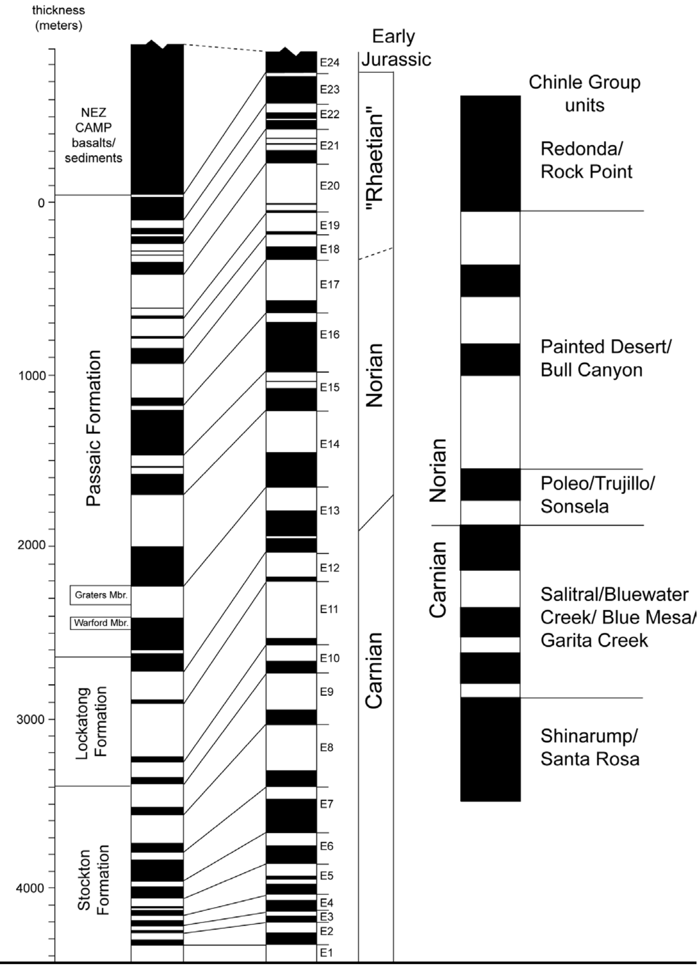

FIGURE 5. Composite magnetic polarity history of the Chinle Group based on available data, compared to the Newark basin polarity stratigraphy, with biostratigraphic datum (Carnian-Norian boundary) indicated (from Lucas et al., 2012).

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