A Middle Triassic paleomagnetic pole for North America

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ABSTRACT

Two stratigraphic sequences were sampled through the early Anisian Anton Chico Member of the Moenkopi Formation in northeastern New Mexico. Two polarities of magnetization are present: a normal-polarity interval succeeded by a reversed-polarity interval and followed by a short normal- and reversed-polarity couplet. Detailed thermal demagnetization (10 to 17 steps) was employed to separate magnetic vectors. The secondary magnetization is largely a direction similar to the present-day and/or axial-field directions. Demagnetization above 520°C reveals a near-horizontal characteristic magnetization. The lithology of the stratigraphic sequence is such that the reversed polarity is contained almost exclusively within coarse sandstone lithologies, and hence, the reversed-polarity characteristic magnetization direction is rarely completely separated from the secondary magnetization. Because of this, the paleopole was calculated from only the lower normal-polarity portion of the section. The pole, calculated from the samples of two localities, is located at 121.4°E, 43.2°N, (α_{95} = 5.3). This Middle Triassic paleopole is in good agreement with published Triassic paleomagnetic poles for cratonic North America and statistically overlaps the Early Triassic paleopoles. The large-scale relative motion during the Triassic between the magnetic pole and the North American plate is constrained by this study to have begun after early Middle Triassic time; it suggests that as much as 10° of apparent-polar wander occurred between the late Anisian–Ladinian (late Middle Triassic) and the middle to late Carnian (early Late Triassic), a time interval of between 11 and 14 m.y.

INTRODUCTION

The Anton Chico Member of the Moenkopi Formation is exposed across northern New Mexico and consists of as much as 100 m of fluvial sandstone, conglomerate, siltstone, and mudstone, lying between rocks of well-established Permian (Guadalupian) age (Artesia Group, San Andres Formation or Glorieta Sandstone; Lucas and Hayden, 1991) and those of Late Triassic age (Santa Rosa Formation or Shinarump Member of Chinle Formation) (Lucas and Hunt, 1987; Lucas and Hayden, 1989). The Anton Chico Member in New Mexico occupies the same stratigraphic position as the Holbrook Member of the Moenkopi Formation in Arizona. The two are readily correlated on the basis of similar lithology and stratigraphic position; their stratigraphic equivalence, moreover, is proven by the recent recognition of identical faunas. The Anton Chico and Holbrook Members both yield fossils of the benthosuchid amphibian *Eocyclotosaurus* and footprints of a large manus *Chirotherium* (Lucas and Morales, 1985; Morales, 1987; Lucas and Hayden, 1989). The presence of *Eocyclotosaurus* establishes an early Anisian age for the Anton Chico Member, as this genus is known from well-established early Anisian deposits in central Europe, including the uppermost Bundsandstein (Rot) of Germany and the Voltzia Sandstone of France (see Lucas and Morales, 1985). The European continental units are readily traced, both through interfingering relationships and palynological biostratigraphy, to the ammonite-dated marine Anisian.

Two stratigraphic sequences within the Anton Chico Member were sampled, both near 34.9°N, 105.7°W, about 5 km west of Clines Corners, New Mexico, along Interstate Highway 40 (Fig. 1). The first section is near a location designated as "Highway Tank" on topographic maps; this section is located on the side of a small mesa, ~175 m north of the interstate highway. The second section is located in a roadcut of the highway, ~1.5 km to the west of the first locality, on a topographic extension of the mesa containing the first locality. At the first section, the entire stratigraphic sequence of the Anton Chico Member present here was sampled; the roadcut exposes only the lower 10 m of the section, all of which was sampled.

The lithology at the sampling sites is fine-grained sandstone interbedded with mudstone in the lower 10 m of the section; at about 10 m above the base of the section, the lithology changes abruptly to coarse-grained, large-scale, cross-bedded, massive sandstones, and this lithology dominates the following 10 m of the section at this locality. This change is marked by a conglomerate (at 10.4 m) that contained part of a skull of *Eocyclotosaurus*, thus establishing a second occurrence of a skull of this early Anisian index taxon within the Moenkopi Formation in New Mexico. The uppermost 2 m of the Anton Chico Member at this locality is largely a partially bleached siltstone and mudstone. The sequence is overlain by conglomeratic sandstones of the Upper Triassic Tecolotito Member of the Santa Rosa Formation.

The reddish-brown deposits of the Anton Chico lie concordantly, but unconformably, on the orangish-red, fine-grained siltstones and sandstones of the Artesia Group, exposed at the

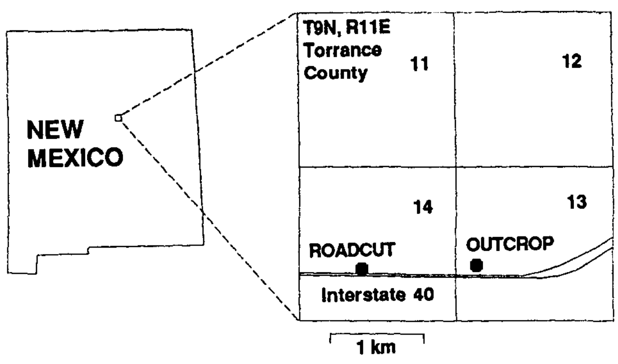

Figure 1. Location of sampling sites along Interstate 40 in north-central New Mexico.

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first locality. Sampling began 0.1 m above that boundary. At the roadcut locality, a fault occurs at the base of the section and appears to lie just under the highway roadbed; sampling at this locality began in the first exposures north of the roadbed. Samples were collected in continuous stratigraphic sequences, at intervals between 0.3 and 0.5 m in all parts of the fairly fine-grained lithologies, that is, medium-grained sandstone, fine sand, siltstone, and mudstone. The coarser sandstones in the upper part of the section were sampled for stratigraphic completeness, but often at larger intervals. At the first locality, 64 samples were collected from 22.3 m, and 38 samples were collected from 10.2 m in the roadcut. The beds at both localities dip about 15° to the northwest (N30°W).

MAGNETIZATION

Natural remanent magnetization (NRM) directions differed between the two localities. At the first locality, NRM directions of the lower portion of this section were clustered (in geographic coordinates) midway between the axial and/or present field directions for this site and an expected normal-polarity, Early Triassic direction for the North American craton (determined from the published studies of the Chugwater Group). The upper portion of this section, which exhibited reversed-polarity magnetization after demagnetization, exhibited very dispersed NRM directions, lying loosely around the present field direction (dec. = 10.9°; inc. = 62.5°) in intermediate directions between the present field and a reversed-polarity direction and in apparent Triassic reversed-polarity directions.

Samples from the roadcut locality had NRM directions in proximity to, but about 10° to the northeast of, the axial dipole field direction (dec. = 0°, inc. = 54°) for this latitude. This difference immediately suggested fairly significant secondary magnetization in the axial field direction at the roadcut locality, more so than in samples from the natural exposure. This is a surprising result because the fresher material revealed by recent man-made exposures usually provides magnetic directions with less secondary magnetization than found in natural exposures. The greater secondary magnetization of this locality may result from proximity to the fault at the section base.

The samples were demagnetized using only thermal demagnetization, because this method is nearly always more effective than alternating field demagnetization in red sedimentary rocks, which invariably have some or all of their magnetization carried by hematite. A pilot series of 12 samples from the main locality and 6 samples from the roadcut were demagnetized in 17 steps from 150 °C to 700 °C. Based on the resulting data, the remainder were demagnetized in 10 steps from 300 °C to 700 °C. The demagnetization trajectories were analyzed for linear portions, using principal component analysis (Kirschvink, 1980).

In general, the present or axial field directions are removed between 20 °C and 520 °C. Between 520 °C and ~680 °C, a near-horizontal magnetization is observed in many samples. This horizontal vector is observed in nearly all normal- and a few reversed-polarity samples and constitutes the characteristic remanent magnetization (ChRM) of these strata. Above ~680 °C, coherent magnetization is not observed. Typical magnetic behavior during demagnetization is shown in Figures 2 and 3; this behavior will be discussed according to the magnetostratigraphic-polarity sequence (shown in Fig. 4).

Generally, a direct correlation is observed between coarseness of lithology and a greater overlap in the stabilities of magnetization vectors. Most samples from the finer grained lower 10 m of the stratigraphic sequences (lower 10 m of locality 1 and entire roadcut section) displayed a narrow range of blocking temperatures,

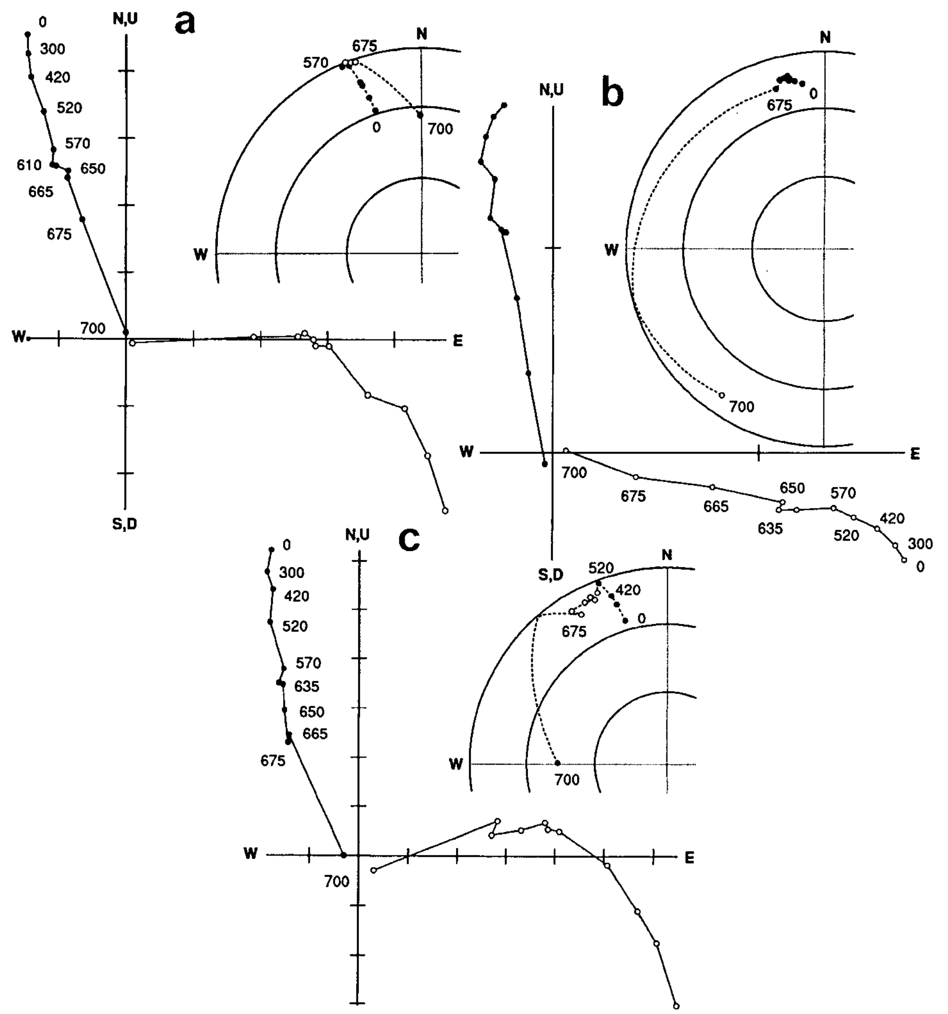

Figure 2. Demagnetization behavior of representative samples of normal polarity. Each sample is shown in both equal-area stereographic projection (geographic coordinates) and orthogonal-axes projection (structurally corrected). The orthogonal-axes projections plot inclination in the plane of the declination; hence, the distance from the origin is a measure of the total intensity of magnetization. Scale divisions on orthogonal axes plots are (a) 1 × 10^{-3} A/m; (b) 5 × 10^{-3} A/m; (c) 5 × 10^{-4} A/m. The horizontal (vertical) components of the magnetization are shown as solid (open) circles. Stereographic projections show lower (upper) hemisphere directions as solid (open) circles.

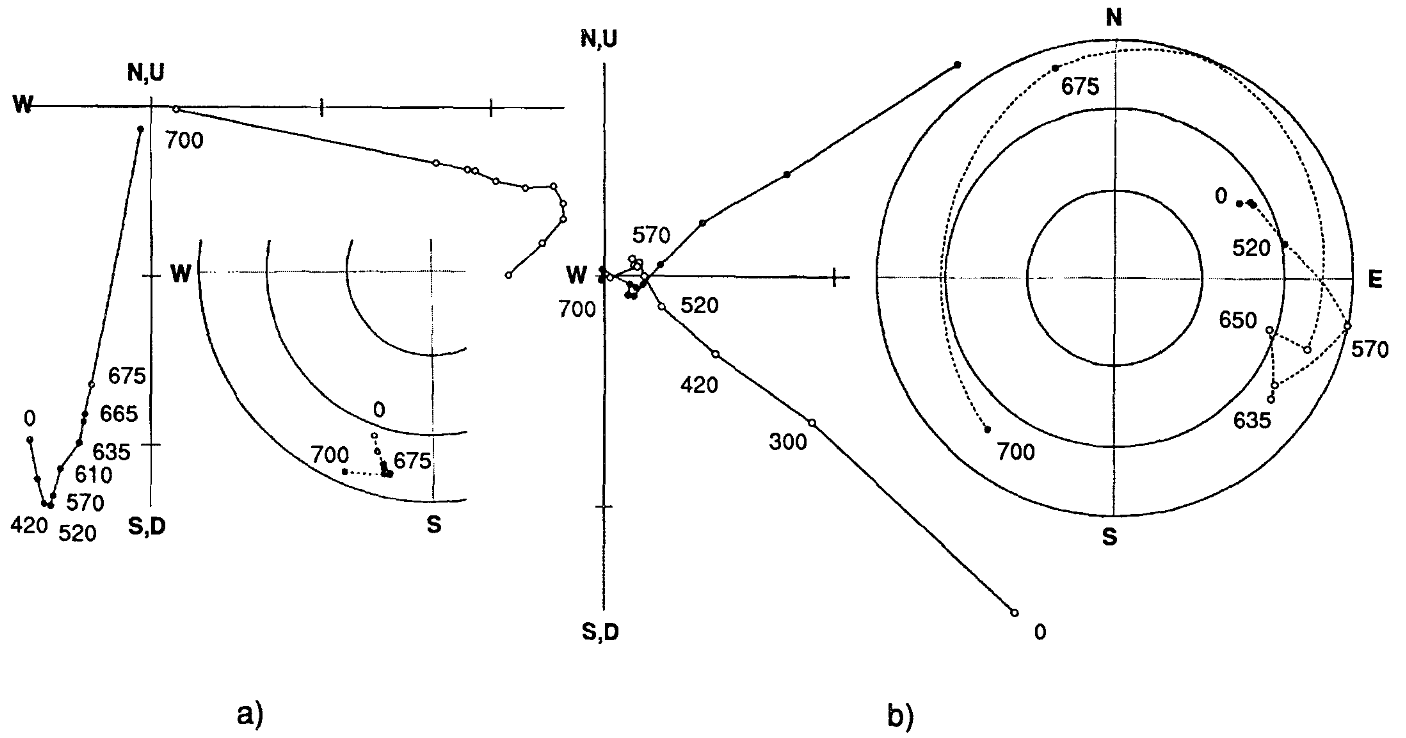

Figure 3. Demagnetization behavior of representative reversed polarity samples. Symbols and conventions as in Figure 2. Scale divisions on orthogonal-axes plots are 5×10^{-3} A/m.

restricted to temperatures largely above 500–600 °C; the dominantly coarse-grained upper 12 m of stratigraphic section exhibit blocking temperatures evenly distributed over the entire range between 20 °C to 675 °C. Samples exhibiting reversed polarity were located almost entirely in coarser grained lithologies, and clear separation of the reversed-polarity characteristic magnetization direction was achieved in only a few samples. Incomplete separation of characteristic and secondary components was true of all samples obtained from above the conglomerate layer described above. Figures 2a–2c show typical examples of samples with normal-polarity ChRM from the lower 10 m of the sections. Figures 3a and 3b display two examples of reversed-polarity ChRM samples; 3a shows one of the few samples with well-defined ChRM, and 3b illustrates a more typical sample with reversed-polarity ChRM.

At about 3.5 m above the base of the section, a placer layer of heavy minerals was encountered within a sandstone bed, very similar to such layers studied elsewhere (Steiner, 1983). Because of the obvious detrital accumulation of iron-oxide grains, samples were taken both in the layer and in the matrix sandstone. Samples of the placer layer showed ChRM directions identical to those of the enclosing sandstone matrix and other beds within this lower normal-polarity interval. Intensities of the ChRM of the samples from the placer layer, however, are at least an order of magnitude higher than other lithologies of this interval, having magnitudes of ~5×10^{-2}A/m. Microscopic examination reveals that the iron-oxide grains of the layer have a detrital outline. The similarity of ChRM directions, coupled with appreciably higher intensities in the placer layer as compared to the other rock types, and the apparent detrital nature of the grains suggests that the magnetization of the layer might be a detrital remanent magnetization (DRM). By inference from this directional similarity, the characteristic remanence of the formation also might be a DRM.

The magnetostratigraphic sequences displayed in Figure 4 show that the lower 10 m of entirely normal-polarity ChRM are followed by ~8.5 m of reversed-polarity ChRM. Above this, normal-polarity ChRM is again observed for 2 m, succeeded by another 1 m of reversed-polarity ChRM, above which the Anton Chico Member is terminated by the unconformity with the overlying Santa Rosa Formation. The polarity change from the lower normal-polarity interval to the succeeding reversed-polarity interval occurs stratigraphically near the top of an interval of mudstone-siltstone. The highest sample, near the top of this mudstone interval, has a well-defined, reversed-polarity ChRM. Two thin sandstone beds that also show well-defined, reversed-polarity ChRM overlie the mudstone. Immediately above these, the conglomerate occurs, and the layers change to the predominance of coarse sandstones discussed above. The boundary between the lower normal- and reversed-polarity intervals definitely occurs within the fine-grained mudstone interval, not at the pronounced lithologic change.

POLE POSITION

Because overlapping stabilities of secondary and primary magnetization are characteristic of nearly all samples above the change to coarse lithologies only samples from the lower part of the Anton Chico Member were used for the calculation of a pole position. Even though finer-grained lithologies occasionally occur within the reversed- and the upper normal-polarity intervals, the separation of ChRM and secondary components is never as clear as it is in the lower fine-grained part of the section. The paleopole, therefore, was calculated from samples of normal-polarity ChRM only, using the samples from the lower normal-polarity interval of both sampling sites.

More than 50% of the samples from each collection of the lower normal-polarity interval display the ChRM as the vector remaining after

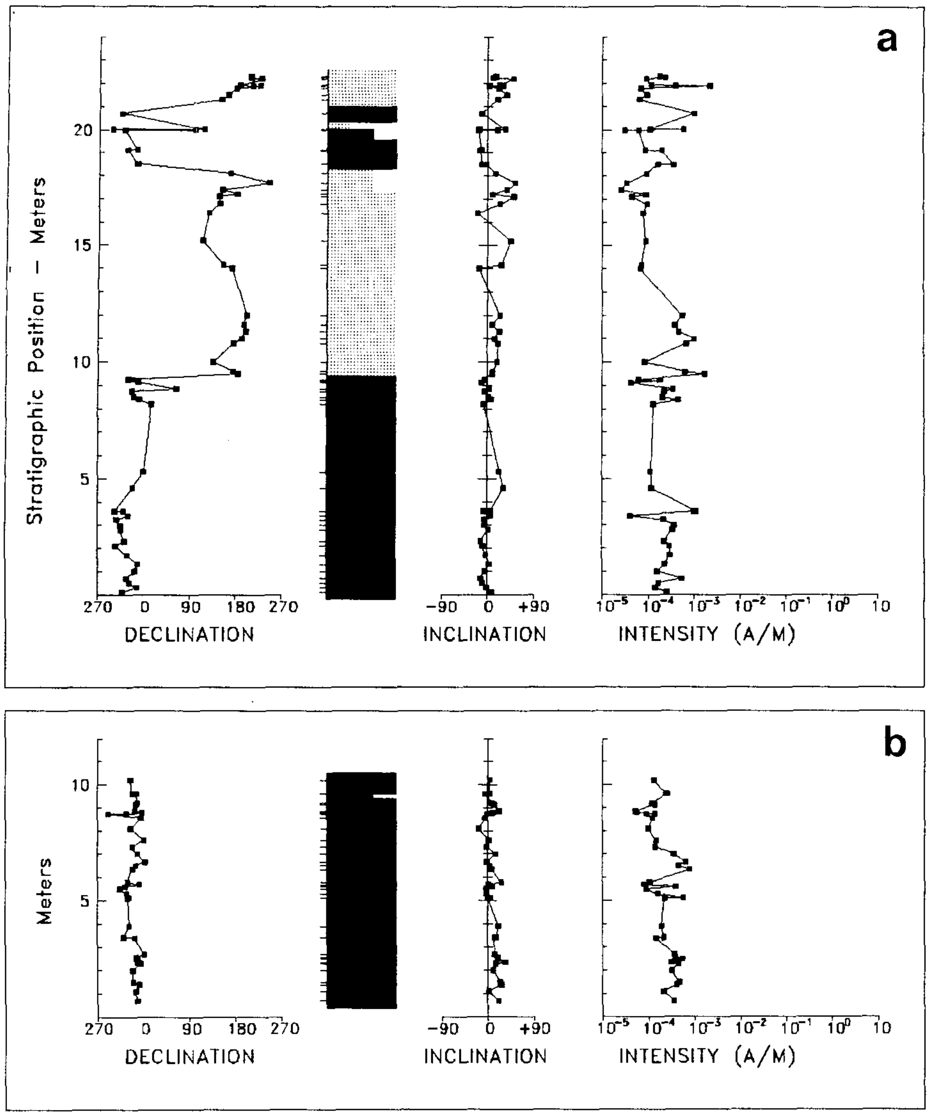

Figure 4. Stratigraphic plots of paleomagnetic data from (a) section 14 of Figure 1 and (b) section 13 of Figure 1. Width of the polarity column denotes certainty of polarity interpretations. Black is normal; stippled is reversed. Postions of the individual samples are indicated on the left side of the polarity column.

heating to the temperature steps of 520 °C and above. These samples display demagnetization paths that trend to the origin of orthogonal axes plots in the 520 °C through 660 °C temperature range. Many of the rest of the samples in this polarity interval display the ChRM direction as the vector removed during heating in this temperature interval. In these samples, linear trends are observed, but they are not to the origin of the ortho-axes plots. The ChRM directions determined by least-squares–line fits that include the origin are termed "$ChRM_{remaining}$"; ChRM directions calculated from the linear portion of demagnetization paths not to the origin are termed "$ChRM_{removed}$."

To ascertain whether the $ChRM_{remaining}$ and $ChRM_{removed}$ were indeed the same, separate mean directions were computed from all calculated vectors of each type, and for each locality. The confidence limits of all four mean directions overlap, indicating that the remaining and subtracted directions are observations of the same vector direction. Although 40 samples displayed the ChRM, only about half of these (21) had errors of <2° associated with the least-squares lines fit to the demagnetization trajectories. Samples with greater errors appeared to show a systematic bias toward the secondary magnetization direction; hence, the pole position for the Anton Chico Member of the Moenkopi Formation was calculated from only those 21 samples (Table 1). This pole was calculated by combining the $ChRM_{remaining}$ and $ChRM_{removed}$ vector directions from both localities and giving unit weight to each. Only one direction per sample was used, and the $ChRM_{remaining}$ directions were favored if both had been calculated from the demagnetization path of a sample. The pole is located at 121.4°E, 43.2°N (n = 21; α_{95} = 5.3°).

This pole position constitutes one of a very few of Middle Triassic age from rocks situated on the North American craton, and the only one from sedimentary rocks. This paleopole from the Anton Chico Member is compared to other Triassic paleopoles for cratonic North America in Figure 5. Poles derived from the Colorado Plateau region have been excluded because of the uncertainty in the amount of rotation the plateau has experienced with respect to cratonic North America. The Anton Chico pole agrees well with the other Triassic poles and statistically overlaps pole of the Early Triassic Red Peak Formation.

The Red Peak pole shown here is that of Shive and others (1984). Three studies of the Red Peak Formation have been published (Grubbs and Van der Voo, 1977; Shive and others, 1984; Herrero-Brevera and Helsley, 1983). Bazard and Butler (1991) argued that the Grubbs and Van der Voo study yields the best determination of the pole position for this formation because individual poles were calculated for each site and a mean calculated from pole positions rather than from vector directions. That pole, however, is derived from only seven individual, stratigraphically separated beds (Grubbs and Van der Voo, 1977, p. 28), but the Shive and others (1984) pole is derived from averaging the individual sample directions from

TABLE 1. ChRM DIRECTIONS OF PALEOMAGNETIC POLE CALCULATION

Declination	Inclination
319.6	7.4
333.0	-10.1
327.8	-13.2
343.9	-5.9
330.1	-2.6
324.7	-12.9
316.1	-6.2
307.9	-5.1
341.0	2.2
338.2	-5.0
339.8	-4.1
329.8	3.3
338.9	4.1
328.4	.2
314.1	-.8
324.8	9.9
340.4	12.0
345.6	8.2
349.3	2.6
321.9	-7.0
306.8	-8.7
305.2	6.5

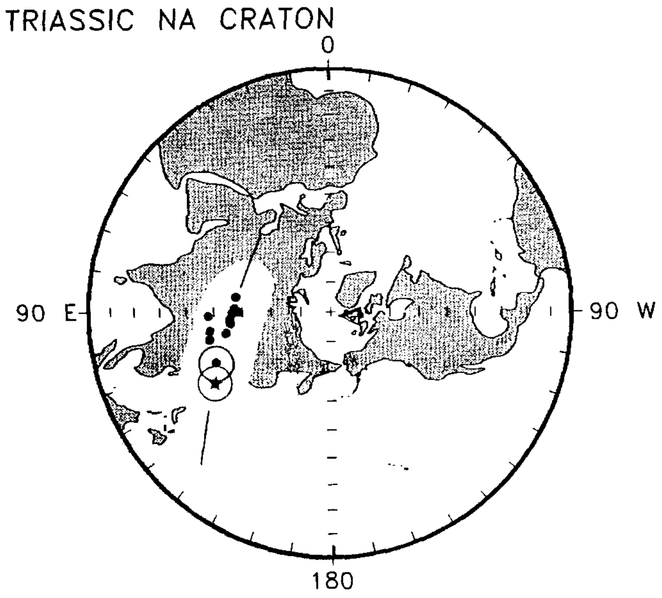

Figure 5. Paleomagnetic pole determined from this study compared with those of all other Triassic paleopoles determined from cratonic North America (Colorado Plateau poles are excluded). The group near 90°E and 55°–60°N consists of the Late Triassic poles of the Redondo Formation (Reeve and Helsley, 1972), Manicougan Structure (taken from May and Butler, 1986), Bull Canyon (Bazard and Butler, 1991), Chinle Formation (Reeve and Helsley, 1972), Newark Hettangian (Witte and Kent, 1990), Popo Agie Formation (Grubbs and Van der Voo, 1977), Newark Carnian-Norian (Witte and Kent, 1989). The poles at <50°N and longitudes of 90°–100° are the Ankarah Formation (Grubbs and Van der Voo, 1977) and Abbott and Agamenticus plutons (Wu and Van der Voo, 1988). The Early Triassic Peak Formation (Shive and others, 1984) and the Anton Chico paleopole of this study (star) are shown with their associated α_{95} circles of confidence.

four of five stratigraphic sequences. These sequences were sampled at 1-m intervals spanning the 200 m of stratigraphic section, providing a data base representing a great many more samplings of the geomagnetic-field direction from the time interval under consideration. The paleopole determination of Shive and others (1984), therefore, is likely to be the better representation of the position of the paleopole at that time. Its derivation, moreover, from four separate sites with different structural corrections clearly speaks for greater confidence that this paleomagnetic pole determination represents the true location of the magnetic pole at that time.

Other Early or Middle Triassic paleopoles reported for cratonic North America are from two Middle to Late Triassic plutons in Maine (Wu and Van der Voo, 1988) and the Early Triassic Ankarah Formation of the western Wyoming thrust belt (Grubbs and Van der Voo, 1977). The Anton Chico pole does not agree with these, however; uncertainties associated with these poles challenge the significance of that discrepancy.

These three poles all lie at latitudes lower than every other Early through Late Triassic pole (Fig. 5). Although this may reflect excursions in the apparent polar wander path (Wu and Van der Voo, 1988), other explanations are equally likely. In all cases, the data sets are dominated by, or are exclusively, reversed-polarity magnetizations. Unremoved recent magnetizations of normal-polarity bias reversed-polarity magnetizations to the effect that lower latitude paleopoles result. This effect is quite evident in the Triassic paleomagnetic poles reported in the 1960s when alternating-field demagnetization was the principal cleaning method for red, sedimentary rocks. As recognized by Wu and Van der Voo (1988), moreover, the Maine plutons also have the irresolvable uncertainty of having no indicators of paleo-horizontal. In the case of the Ankarah Formation pole, another possible cause of the deviation could be its structural setting within the Wyoming thrust belt. Although arguments against structural disturbance were presented, the uncertainty was not removed. The Ankarah Formation, furthermore, is the more seaward facies of the continental, sebkah-deposited Red Peak Formation; hence, these formations are equivalent in age and should have recorded the same paleopole position. The 28-sample population yielding the Ankarah paleopole, nevertheless gives a significantly different pole position than the three individual studies of the Red Peak Formation, which are uniformly in agreement (yielding kappa value of 1835 on the mean of the three; Steiner, 1986). All of these uncertainties cast doubt on whether the deviation of Maine plutons and the Ankarah paleomagnetic poles from the track that is formed by all other Triassic poles is significant.

Ignoring these three paleopoles, the majority of the paleopoles in Figure 5 are arrayed in an elongate linear track. North American Early and Late Triassic paleopoles long have shown a difference amounting to between 20° and 30° of separation, indicating that a significant amount of apparent polar motion relative to North America occurred sometime during the Triassic. The recent publication of several paleomagnetic poles for the Late Triassic has partially filled the pronounced gap that previously existed between Early and Late Triassic poles. A significant gap, nevertheless, exists between the oldest determined Late Triassic paleomagnetic poles and those of the Early Triassic. The position of the Middle Triassic Anton Chico paleomagnetic pole of this study, in proximity to the Early Triassic pole, indicates that the Triassic apparent polar wander or plate motion did not begin until after the early Middle Triassic (post–early Anisian). The further implication is that appreciable apparent polar wander occurred during the Middle Triassic.

Estimation of the rate of this apparent polar wander/plate motion is difficult because Triassic time scales are not well constrained. The compilation by Forster and Warrington (1985) is the most detailed summary; Haq and others (1988), Harland and others (1990), and Odin and Odin (1990) have published more recent reviews, but discussions of the selections of reliable ages are much less comprehensive. Taking all four time scales into consideration, the location of the Anton Chico paleopole suggests that as much as 10° of apparent polar motion occurred in a time period of between 11 and 14 m.y. This implies a relatively fast rate of North American plate motion (as much as 8–10 cm/yr). Another indication of the reality of fast plate motion at this time might be the pronounced paucity of Middle Triassic sedimentary rocks on this continent; sufficient rapidity of plate motion may tend to elevate the continental land mass and induce an erosional sedimentary regime to prevail.

CONCLUSIONS

The early Middle Triassic Anton Chico Member of the Moenkopi Formation was sampled at two localities in northeastern New Mexico. A sequence of normal and reversed polarity was observed. A paleomagnetic-pole position was calculated from the fine-grained part of the section (consequently from samples of only normal polarity) and is located at 121.4°E, 43.2°N (α_{95} = 5.3°). This paleopole statistically overlaps the Early Triassic pole position for cratonic North America. A gap between these poles and the Late Triassic paleopoles indicates that substantial apparent polar wander, reflecting North American plate motion, occurred during Middle Triassic time. The Anton Chico paleopole constrains the up to 10° of apparent wander to have occurred in a time interval of 11—14 m.y., between the late Middle Triassic (late Anisian–Ladinian) and early Late Triassic (middle to late Carnian) time.

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