A middle Carnian to early Norian (~225 Ma) paleopole from sediments of the Newark Basin, Pennsylvania

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ABSTRACT

Paleomagnetic study of the middle Carnian Stockton Formation, upper Carnian Lockington Formation and the lower part of the Norian Passaic Formation from 24 sites along 3 traverses perpendicular to strike in the Newark Basin of eastern Pennsylvania shows that two hematitic magnetizations can be isolated from these rocks. Thermal demagnetization experiments reveal a distributed unblocking temperature (typically 300 to 680 °C) magnetization with uniformly downward and northerly directions, and a high unblocking temperature (660 °C and above) magnetization with shallow northerly (normal polarity) and southerly (reversed polarity) directions. On the basis of a correlatable magnetic polarity stratigraphy between 3 traverses spanning 40 km along strike, and within-site directional scatter similar to that expected from paleosecular variation, the high temperature magnetization was most probably acquired at or near the time of deposition. The pole calculated from the high unblocking temperature magnetization (53.6°N, 101.6°E, A95 = 4.8°) is consistent with other Late Triassic poles and indicates a paleolatitude of 3.8°N ± 3.0°. The lower unblocking temperature magnetization is an overprint acquired at about the same time as the Jurassic Newark trend igneous N2 pole magnetization.

INTRODUCTION

Although the apparent polar wander path (APWP) for North America is relatively well documented from the late Carboniferous to the Recent, controversy has emerged in recent syntheses regarding the Late Triassic and Early to Middle Jurassic portion of the pole path. The running mean method of constructing a representative APWP (for example, Irving and Irving, 1982) assumes only that apparent polar motion has occurred relatively slowly over time

scales of tens of millions of years, but it depends on the availability of a sufficient number of paleopoles in every averaging time window to form a representative mean. The paleomagnetic Euler pole method (Gordon and others, 1984) brings an *a priori* model of plate motion to the problem by assuming that the Euler pole which describes a plate's motion with respect to the paleomagnetic axis remains fixed for long periods (on the order of 100 m.y.) between plate-motion reorganizations; this model predicts that an APWP should consist of a few small circle tracks concatenated by hairpins or cusps. This method depends less upon obtaining a large number of paleopoles and allows one to be more critical in selecting the data on which the APWP is based.

Application of these two methods to paleopole data for North America yields very similar APWP's from late Carboniferous to about the Middle Triassic, and from Late Jurassic to Recent. In the Late Triassic to Middle Jurassic (ca 220 Ma to 160 Ma), however, there are disagreements by as much as 12°, which contribute considerable uncertainty to the interpretation of the motions of Cordilleran terranes in this time interval (May and Butler, 1986). In part these differences are the result of the different methods, but at least equally important are the differences in the data sets used in the construction of the APWP.

Our knowledge of North American apparent polar wander during Late Triassic to Middle Jurassic time relies heavily on poles from two sources: the Triassic and Jurassic sediments of southwestern North America and the Jurassic igneous rocks of eastern North America. The different APWP syntheses utilize both of these data sources, but to various extents. Late Triassic and Early Jurassic red beds from the Southwest are represented by three poles (with only one from the Colorado Plateau) in the Irving and Irving (1982) synthesis and by four poles (with 3 from the Colorado Plateau) in Gordon and others (1984). Although the Triassic and Jurassic sediments of the southwestern

TABLE 1. SITE LOCATIONS AND STRUCTURAL ATTITUDES

Site	Long. (W)	Lat. (N)	Strike	Dip
TPA	75°27.07'	40°11.59'	220°	13°W
TPB	75°26.83'	40°12.53'	272°	15°N
TPC	75°26.85'	40°13.62'	245°	12°N
TPD	75°27.44'	40°14.98'	261°	21°N
TTA	75°23.66'	40°21.38'	230°	08°N
TTB	75°23.37'	40°20.82'	222°	08°W
TTC	75°22.78'	40°19.56'	222°	10°W
TTD	75°22.30'	40°18.23'	196°	16°W
TTE	75°20.59'	40°14.55'	204°	09°W
TTF	75°20.11'	40°13.75'	210°	10°W
TTG	75°19.48'	40°12.68'	270°	10°N
TTI	75°18.84'	40°11.39'	252°	12°N
TTJ	75°18.42'	40°10.28'	230°	10°N
TTK	75°17.62'	40°09.22'	218°	22°W
	75°17.02'	40°07.53'	220°	15°W
TDA	75°04.42'	40°31.50'	148°	06°W
TDB	75°04.27'	40°29.43'	193°	10°W
TDC	75°04.23'	40°28.35'	223°	12°W
TDD	75°04.40'	40°27.05'	229°	12°N
TDE	75°04.20'	40°26.48'	244°	12°N
TDF	75°02.90'	40°24.82'	224°	11°W
TDG	75°01.12'	40°24.22'	218°	12°W
TDH	74°59.42'	40°24.18'	218°	12°W
WCA	74°58.00'	40°26.76'	228°	13°N

United States are well exposed and uncomplicated structurally, two problems cloud the interpretation of paleopoles from these rocks. Several authors have suggested on the basis of regional tectonic studies (Hamilton, 1981) and paleomagnetic studies (Steiner, 1986; Bryan and Gordon, 1986) that the Colorado Plateau had rotated 4° to 11° clockwise sometime after the Carboniferous and before the Cretaceous. Secondly, the age assignments and correlations of Triassic and Jurassic rocks in the southwest United States are often complicated by local and regional unconformities of imprecisely known duration (Pipiringos and O'Sullivan, 1978).

The Newark igneous rocks of eastern North America are represented by ten poles in the Irving and Irving (1982) synthesis and by only two aggregate poles in Gordon and others (1984). Although the Newark igneous rocks most probably have not suffered rotations of the order of those suspected for the Colorado Plateau, their ages are in fact problematic. Even though the extrusive rocks of the Newark are well constrained biostratigraphically (Cornet and others,

Figure 1. Geologic sketch map (based on Lytle and Epstein, 1987) showing the location of sampling sites. pC = Precambrian basement, Pz = Paleozoic basement, Ts = Stockton Formation, Tl = Lockatong Formation, JRp = Passaic Formation, Jd = Diabase intrusions.

1973) to within the Hettangian (204 to 208 Ma according to the time-scale of Palmer, 1983), they span perhaps only 0.5 m.y. (Olsen and Fedosh, 1988), making them of limited use in defining any appreciable portion of the APWP. The igneous intrusions are generally thought to be Early to Middle Jurassic in age but are uniformly difficult to date radiometrically (Sutter and Smith, 1979). The APWP syntheses cited above assign dates to the intrusions that range from about 200 to 170 Ma. Recently, Sutter (1988) has suggested that the potassium-argon geochronometer of Newark igneous rocks has been variably disturbed by a hydrothermal argon loss event at about 175 Ma. This event might have similarly reset the magnetization of the igneous rocks at that time, either partially or completely. Compounding the dating difficulties, one is also uncertain of the attitude of the intrusive rocks and their hosts at the time of magnetization.

The red clastics of the Newark Supergroup (Olsen, 1978) are a potential alternative and

independent source of Triassic and Jurassic paleomagnetic poles for the time interval encompassing the APWP controversy. Newark Supergroup sediments, ranging up to 8 km in thickness, fill nearly 20 basins along the eastern coast of North America. Although previously thought to be confined to the Triassic, the Newark Supergroup has been shown on the basis of palynological biostratigraphy (Cornet and others, 1973; Cornet and Olsen, 1985) to span from the Anisian (Middle Triassic) through the Toarcian (late Early Jurassic), or 235 Ma to 187 Ma by the timescale of Palmer, 1983. After lacustrine and fluvial deposition in half grabens, the sediments have by and large experienced only gentle deformation in local folds and presently tilt 10° to 15° toward the boundary faults.

Much of the paleomagnetic study of the Newark Supergroup has concentrated on the Jurassic igneous intrusive and extrusive rocks (for example, deBoer, 1968; Smith and Noltmeyer, 1979; or the compilation of Irving and Irving, 1982). Results of the paleomagnetic

study of sediments of the Newark and Hartford Basins have been reported in several papers (DuBois and others, 1957; Opdyke, 1961), abstracts, and unpublished theses, but McIntosh and others' (1985) study of the Carnian to Hettangian sediments of the Newark Basin is the only comprehensive published study of the paleomagnetism of Newark Supergroup sediments to include thermal demagnetization. Although these authors were able to produce a broadly correlative magnetostratigraphy for the basin, an unremoved magnetic overprint prevented them from obtaining meaningful paleopoles.

Because the Newark Basin sediments are now known to span a critical time in the APWP controversy, we decided to more fully test the suitability of the Newark for pole studies with detailed progressive thermal demagnetization in the hope of separating an early formed remanence from any later remagnetization. The Carnian and early Norian (~225 Ma) portion of the North American APWP is relatively uncontroversial and was chosen as the interval in which

Figure 2. Representative thermal demagnetograms of Newark Basin sediments. Demagnetization steps are in degrees Centigrade. Closed and open circles represent projection of vector end points onto the present horizontal and north-south vertical planes, respectively.

to test the reliability of the sedimentary paleomagnetic record of the Newark Basin. By choosing to sample the lowest strata in the Newark Basin, we have tried to avoid potential problems with local thermal remagnetizations due to the intrusions higher in the section and local rotations associated with possible strike-slip along the western border fault (Sanders, 1962; Ratcliffe and Burton, 1985; Van Fossen and others, 1986), while still confronting the issue of regional remagnetizations by sampling the oldest sediments.

SAMPLING

The Newark Basin, located in eastern Pennsylvania, northern New Jersey, and southern New York, is the largest and best known of the Triassic-Jurassic rift basins along the eastern coast of North America associated with the early Mesozoic opening of the Atlantic Ocean. Samples were taken from 24 sites distributed along three traverses through the middle Carnian Stockton Formation, the upper Carnian Lockatong Formation, and the lower part of the Norian Passaic Formation in eastern Pennsylvania (Table 1 and Fig. 1). The traverses were chosen perpendicular to strike along the Pennsylvania Turnpike, Delaware River, and Perkiomen Creek which afford good exposure (~20% outcrop) in the southwestern portion of the basin, remote from the thick and areally extensive Palisades Sill, which underlies much of the northwestern portion of the basin. Sites, which spanned 10 to 20 m of strata with 5 to 7 oriented cores per site, were spaced approximately every 300 m stratigraphically along each traverse. A stratigraphic section of approximately 3.5 km was sampled in this study.

RESULTS

Initial natural remanent magnetizations (NRM's) ranged in intensity from 1 to 100 mA/m and were directed primarily northward and down with a smattering of southerly directions. Alternating field (AF) demagnetization to 100 mT was attempted, but the method was not sufficient to resolve magnetization components. Therefore, each core sample (1 to 3 specimens) was thermally demagnetized in 15 to 23 incremental temperature steps to 700 °C. Irreversible thermo-chemical alteration of the samples was monitored by measuring the room temperature susceptibility as thermal demagnetization progressed.

Aside from a generally spurious magnetization removed below about 200 °C, the NRM of these samples consists of two components as defined by linear vector end-point demagnetization trajectories (Fig. 2). Component B is typically unblocked between 300 °C and up to 680 °C

Figure 3. Site mean directions of B and C components plotted on equal-area stereographic projections. Closed and open symbols represent directions below and above horizontal, respectively. The X's with their attendant ellipses represent the mean component directions and their α_{95} envelopes. Triangles show the present-day field direction in the sampling area.

and invariably has a moderately downward and northerly direction (Fig. 3). At high demagnetization levels, usually above 660 °C, a final C component magnetization is revealed which has either a northerly or southerly shallow direction (Figs. 2, 3).

The high maximum unblocking temperatures of both the B and C components and the very high coercivities indicated by AF demagnetization and isothermal remanent magnetization experiments (Fig. 4) suggest that the NRM of these rocks is carried predominantly by hematite. In reflected and transmitted light, isolated grains of subhedral specular hematite with diameters of 10 to 40 microns are present in addition to a reddish, very fine grained interstitial matrix. These observations of mineralogy and grain relationships are very similar to those reported by McIntosh and others (1985) for Newark Basin red beds.

The directions of the B and C components were estimated for each sample through the application of the principal components analysis method (Kirschvink, 1980). Mean directions were generated at the individual core level, and then the site level for over-all analysis using standard Fisherian statistics (Table 2). Only two

sites (TTA and TTK) failed to produce any interpretable data (TTA was located within 100 m stratigraphically of a large diabase intrusion and was highly altered; TTK was sited in a light gray, coarse arkosic sandstone of the Stockton Formation, which was sampled in a futile attempt to sample the oldest sediments available). The C component could not be resolved at 3 other sites (TTD, TDG, and WCA) because of a very dominant (and easily isolated) B component; however, the remaining 19 sites had at least 3 core estimates of both the B and C components.

INTERPRETATION

C Component

The C component is interpreted to be of normal polarity at 8 sites and reversed polarity at 11 sites. At no site are both normal and reversed C components observed. Although presently described on the basis of only 19 sites spaced at intervals of several hundred meters, the magnetic polarity stratigraphy is consistent between the three traverses (Fig. 5). The reversed magnetizations of the Stockton and

Figure 4. IRM acquisition (triangles) and the thermal demagnetization of IRM (squares) of a sample from site TTC in the lower Passaic Formation.

Lockatong extend into a N-R-N polarity sequence in the lower Passaic Formation.

Although McIntosh and others (1985) sampled the northern half of the basin where we did not, both studies sampled the upper Lockatong and lower Passaic. Where the two overlap stratigraphically, the studies are fairly consistent, but several discrepancies are noted. The reversed interval we find associated with the Graters

Member of the Passaic Formation (Fig. 5) probably corresponds to the mixed polarities McIntosh and others (1985) also observed in the red units on either side of the Graters Member (at their localities 4 and 7). Along the Delaware River, we find only reversed polarity at site TDE (in the Prahl's Island Member of the Lockatong Formation [Olsen, 1986]) and below, whereas McIntosh and others (1985) reported

normal polarities from 2 closely spaced sites about 100 m stratigraphically below site TDE (their localities 1 and 2 in the First Thin Red and First Thick Red of McLaughlin [1943] and Van Houten [1969, 1987], which are equivalent to the red parts of the Skunk Hollow and Tohicken Members of the Lockatong, respectively [Olsen, 1986]). Because of our relatively large site spacing in this part of the section, it is possible that we have missed a short normal interval between sites TDE and TDF; alternatively, the results of McIntosh and others (1985) from these sites are overprinted.

With all 19 sites converted to common (normal) polarity, the mean C component direction is Declination/Inclination (α_{95}) = $3.3^\circ/15.1^\circ$ (5.9°) in geographic, and $1.8^\circ/7.5^\circ$ (6.0°) in bedding coordinates (Table 3). No fold test is possible due to insufficient variation in bedding attitudes. The corresponding paleopole in either geographic (latitude/longitude = $57.4^\circ\text{N}/98.6^\circ\text{E}$) or tilt-corrected ($53.5^\circ\text{N}/101.6^\circ\text{E}$) coordinates, however, does not correspond to any Jurassic or younger portion of any APWP for North America (Table 3 and Fig. 6). This observation, together with the apparent 40 km along-strike continuity of the magnetic polarity stratigraphy, leads us to believe that the C component was acquired nearly penecontemporaneously with the deposition of the sediments in the Carnian and early Norian. Four polarity intervals are discernable, with estimated durations of 1 to 3 m.y., from the middle Carnian to lower Norian Stockton, Lockatong, and Passaic Formations (numerical ages range ~228 to 220 Ma). The paleomagnetic data indicate a paleolatitude of $3.8^\circ\text{N} \pm 3.0^\circ$, consistent with the tropical paleoclimatic setting of the Newark Supergroup (Olsen, 1986).

TABLE 2. SITE MEANS

Site	B Component								C Component							
	n	k	α_{95}	Geo		Bed		n	k	α_{95}	Geo		Bed			
				Dec	Inc	Dec	Inc				Dec	Inc	Dec	Inc		
TPA	5	54	10.5	13.3	33.3	6.8	26.8	5	16	20.0	198.2	-29.0	192.3	-23.6		
TPB	5	148	6.3	13.2	30.8	12.0	16.0	4	17	23.3	353.7	20.8	354.1	6.0		
TPC	4	516	4.0	350.8	54.2	347.7	42.7	5	65	9.6	187.4	-9.8	186.9	0.4		
TPD	5	224	5.1	359.8	41.4	358.0	20.5	5	17	19.0	339.4	25.7	340.5	5.1		
TTB	4	41	14.5	8.5	40.4	3.5	35.8	5	18	18.3	10.4	30.7	6.8	26.3		
TTC	5	105	7.5	355.0	49.8	348.5	42.1	3	30	22.8	191.0	-21.0	188.2	-15.7		
TTD	5	152	6.2	3.8	33.3	354.5	28.8	5	48	11.2	347.7	17.0	344.4	9.0		
TTE	4	68	11.2	2.9	17.9	0.5	14.5	4	444	4.4	353.9	8.0	353.1	3.5		
TTF	5	49	11.1	13.0	26.5	8.6	23.2	5	46	11.3	2.5	6.3	1.8	1.7		
TTG	5	68	9.3	0.3	43.5	0.2	33.5	4	51	13.0	187.5	-1.9	187.5	8.0		
TTH	3	18	29.6	353.7	41.4	352.1	29.6	4	15	24.9	175.3	-19.3	174.7	-7.6		
TTI	4	57	12.3	5.3	44.2	359.5	36.8	4	33	16.3	195.5	-0.4	195.9	5.2		
TTJ	3	28	23.8	10.0	41.5	357.1	28.9	3	36	20.9	196.9	-7.1	195.8	1.1		
TDA	7	804	2.1	7.6	35.4	4.0	39.1	6	53	9.3	0.6	14.6	359.2	17.9		
TDB	7	225	4.0	359.5	41.1	351.6	38.2	5	36	12.8	185.5	-15.4	182.9	-14.0		
TDC	6	340	3.6	2.9	41.1	356.3	32.9	4	39	15.0	3.3	23.1	0.2	15.2		
TDD	6	355	3.6	3.9	38.6	358.7	29.2	0								
TDE	6	160	5.3	4.7	50.7	358.9	40.1	5	23	16.4	188.7	-18.0	187.1	-8.0		
TDF	3	159	9.8	9.0	53.7	358.8	46.6	4	33	16.2	197.0	-14.9	194.8	-9.8		
TDG	5	86	8.3	19.4	45.0	9.3	40.1	0								
TDH	5	32	13.7	1.1	38.7	354.8	31.2	3	9	43.2	168.6	0.0	169.2	9.0		
WCA	15	43	5.9	5.2	42.5	358.1	33.1	0								

Geo, magnetization direction before structural correction; Bed, magnetization direction after structural correction; n, number of independently oriented cores; k, precision parameter; α_{95} , radius of 95% cone of confidence of site mean direction in degrees; Dec, declination in degrees; Inc, inclination in degrees.

B Component

The northward and down B component directions yield a mean for the 22 sites in present geographic ($5.0^\circ/40.4^\circ(3.8^\circ)$) or bedding ($359.3^\circ/32.4^\circ(3.9^\circ)$) coordinates significantly shallower than either the axial dipole (59°) or the present-day geomagnetic field inclination (69°) at the sampling locality. Nevertheless, the uniform normal polarity of the component, together with the lower unblocking temperature, suggests that the B component is a secondary magnetization, acquired after the C component.

As for the C component, a fold test is inconclusive because of insufficient variation in bedding attitude; hence further constraints on the age of the B component must be indirect. The B component paleopole, whether considered in the geographic ($72.7^\circ\text{N}/89.8^\circ\text{E}$) or bedding ($67.6^\circ\text{N}/106.9^\circ\text{E}$) frame of reference, is significantly different from accepted pre-Jurassic or post-Middle Jurassic paleopoles or

TABLE 3. MEAN DIRECTIONS AND POLES

	N	Geo								Bed							
		k	α_{95}	Dec	Inc	K	A_{95}	Long.	Lat.	k	α_{95}	Dec	Inc	K	A_{95}	Long.	Lat.
B component:																	
All	22	66	3.8	5.0	40.4	86	3.4	89.8	72.7	65	3.9	359.3	32.4	100	3.1	106.9	67.6
C component:																	
All	19	33	5.9	3.3	15.1	46	5.0	98.6	57.4	32	6.0	1.8	7.5	50	4.8	101.6	53.5
C_n	8	43	8.6	356.4	18.5	58	7.3	111.6	59.1	45	8.4	354.8	10.7	68	6.8	113.4	54.9
C_r	11	38	7.5	188.3	-12.6	59	6.0	90.1	55.4	36	7.7	186.8	-5.0	64	5.7	93.6	51.8

C_n , sites with normal polarity C components; C_r , site with reversed polarity C components; Geo, magnetization direction before structural correction; Bed, magnetization direction after structural correction; N, number of site means; k, precision parameter for mean directions; α_{95} , radius of 95% cone of confidence for mean directions in degrees; Dec, declination in degrees; Inc, inclination in degrees. Virtual geomagnetic poles calculated from site mean directions were used as data to calculate mean pole positions. K, precision parameter for mean poles; A_{95} , radius of 95% cone of confidence in degrees on pole positions; Long., East longitude in degrees of mean pole position; Lat., North latitude in degrees of mean pole position.

APWP interpretations (Fig. 6). This suggests that the B magnetization is Early or Middle Jurassic in age.

Resolution of Components

McIntosh and others (1985) reported that their Newark red-bed paleomagnetic data contain "unremovable" Cenozoic remanence components which compromise the usefulness of these sediments for paleopole studies. This conclusion was to a very large extent based on an analysis of the sample remanence directions after thermal demagnetization at only 550 °C. The results from progressive demagnetization to

higher temperatures we obtained (as well as similar results for 6 samples described as representative in McIntosh and others [1985]), however, clearly show that a treatment level of 550 °C is generally not sufficient to isolate components of magnetization in these rocks. As described above, more complete demagnetization reveals two ancient components of magnetization (B and C) in most samples, neither of which conform in direction with known Cretaceous or Cenozoic paleomagnetic directions for North America.

Nevertheless, despite the linearity of the vector end-point diagrams (as shown for example in Fig. 2), which would seem to indicate that the B

Figure 5. Magnetic polarity stratigraphy of the Carnian-Norian sediments of the Newark Basin. The Newark Basin formations (S = Stockton Formation, L = Lockatong Formation, P = Passaic Formation) are correlated at the lithologically distinct Graters Member (G) of the Passaic Formation and to Late Triassic stages according to Cornet and Olsen (1985) and Olsen (1986), with numerical ages of the Triassic age boundaries from Palmer (1983). For each stratigraphic section, the left column (a) indicates the formations sampled at each site and their contacts, the middle column (b) shows the latitude of C component site virtual geomagnetic poles (relative to the mean tilt-corrected C component paleopole), and the right column (c) shows our interpretation of the polarity stratigraphy (black = normal polarity; white = reversed polarity).

Figure 6. Newark paleomagnetic pole positions compared to selected Triassic and Jurassic paleopoles and APWP interpretations for North America. Pole positions determined in this study of Carnian to Norian (~225 Ma) sediments of the Newark Basin shown (squares) with their 95% confidence envelopes are as follows: the C component pole in bedding coordinates (Cb), the B component pole in geographic coordinates (Bg) and the B component pole in bedding coordinates (Bb). For comparison, mean poles from the igneous intrusions of the Newark and Gettysburg Basins are also plotted (Ib, in bedding coordinates and Ig, recalculated into geographic coordinates from data in Beck, 1972). Heavy lines show relevant segments of the APWP interpretations of Irving and Irving (1982) (labeled II) and Gordon and others (1984) (labeled GCO), with 175 Ma and 225 Ma points indicated on each. The solid circles denote some of the principal Late Triassic or Jurassic paleopoles used in their syntheses and discussed in the text: P = Popo Agie (cited as Norian-Carnian in GCO), CH1 = Chinle Formation, Redonda Member (cited as Late Triassic in GCO), CH2 = Chinle Formation, Church Rock Member (cited as Norian in GCO), MN = Manicouagan impact (cited as 215 ± 5 Ma in GCO), W = Wingate Formation (cited as Sinemurian in GCO), K = Kayenta Formation (cited as Pliensbachian in GCO), N1 = early Newark trend igneous (cited as 195 ± 5 Ma in GCO), N2 = late Newark trend igneous (cited as 179 ± 3 Ma in GCO), WM = White Mountain intrusives (cited as 180 Ma in II), AI = Anticosti Island (cited as 178 Ma in II), S = Summerville (cited as late Callovian in GCO and in Pippingos and O'Sullivan, 1978), CV = Canelo Volcanics (cited as 151 ± 2 Ma in GCO). Additional poles are from Corral Canyon in Arizona (CC, cited as 172 ± 5.8 Ma by May and others, 1986) and the Abbott (Ab) and Agamenticus (Ag) plutons of Maine, with radiometric ages of 221 Ma and 222 Ma, respectively (Wu and Van der Voo, 1987).

and C components can be well separated, there are indications of some complexities in the resolution of the magnetizations. For the C components, we noted that the normal and (inverted) reversed polarity means differ by 13° (in either geographic or bedding coordinates) which is significant at the 95% confidence level (Fig. 3). The difference from antipodality is mainly in the mean declinations ($\Delta_{Dec} = 12.0^\circ \pm 9.1^\circ$, in bedding coordinates), whereas the absolute mean inclinations are not statistically different ($\Delta_{Inc} = 5.7^\circ \pm 9.0^\circ$, in bedding coordinates), using 95% confidence limits calculated by the method of Demarest (1983).

If the lack of antipodality is attributed to an unremoved contaminating component, then it should be oriented somewhere along the great circle joining the normal and reversed C component means, that is, shallower than about 25° with westerly declination. This locus of possible contaminating components certainly does not include the present field nor any known Triassic or younger paleomagnetic directions from North America, including the B component. It is difficult to imagine a bias in the magnetization process which would be sensitive to the polarity of the magnetization. Alternatively, the time-averaged geomagnetic field in the Late Triassic might have contained a standing, nonaxial component. If this were the case, one might expect to find that other coeval paleomagnetic studies from North America show a similar lack of antipodality. An asymmetry of the same sense, although not significant at the 95% confidence level, is present in Steiner and Helsley's (1974) study of the Early Jurassic Kayenta Formation (for 3 normal and 4 reversed intervals, $\Delta_{Dec} = 8.4^\circ \pm 16.5^\circ$ and $\Delta_{Inc} = 1.7^\circ \pm 15.4^\circ$). No asymmetry in declination, however, was observed in Reeve and Helsley's (1972) study of the Late Triassic Chinle Formation (for 3 normal and 3 reversed intervals, $\Delta_{Dec} = 1.8^\circ \pm 15.4^\circ$ and $\Delta_{Inc} = 15.7^\circ \pm 15.3^\circ$).

Regardless of the cause of the effect, the similar numbers of normal and reversed sites in our study should average out bias from the calculation of the over-all C component mean direction. For comparison, the mean of the (inverted) reversed and normal site subsets in tilt-corrected coordinates (Dec = 000.8°, Inc = 07.9°, N = 2) is within 1° of the mean of all sites (Dec = 001.8°, Inc = 7.5°, N = 19).

A different sort of polarity-dependent bias in direction is observed in the B component in either the geographic or bedding coordinate systems. For example, the geographic B component mean direction (006.6°/33.5°(6.3°), N = 8) from the subset of sites with a normal polarity C component, and the B component mean direc-

tion ($002.3^\circ/44.9^\circ(4.7^\circ)$, $N = 11$) from the subset of sites with a reversed polarity C component, differ by $11.9^\circ \pm 7.9^\circ$ but mainly in inclination ($\Delta_{Dec} = 4.3^\circ \pm 7.9^\circ$ and $\Delta_{Inc} = 11.4^\circ \pm 6.1^\circ$). The great circle passing through the means of these two subsets of B component directions lies very near the mean C component direction. This suggests that the unblocking spectrum of the C component in part overlaps and contaminates the B component spectrum. A similar contamination of the low-temperature magnetizations by their associated high-temperature components, referred to as "underprinting," has been noted in Paleozoic rocks (Miller and Kent, 1988). Because we have B component site means from nearly equal numbers of sites with normal and reversed C components, the effect should be averaged out in the overall B component mean. This is confirmed in the observation that the mean of the reversed and normal site subsets in geographic coordinates ($Dec = 004.6^\circ$, $Inc = 39.2^\circ$, $N = 2$) and the mean of all sites in geographic coordinates ($Dec = 005.0^\circ$, $Inc = 40.4^\circ$, $N = 22$) are only about 1° apart.

DISCUSSION

The NRM of the Carnian and early Norian red beds of the Newark Basin is apparently composed of two components of magnetization, both carried by hematite: a high unblocking temperature C component with a regionally consistent polarity reversal stratigraphy, and a lower and distributed unblocking temperature B component of uniformly normal polarity. The within-site and between-site directional scatter of the C component is significantly greater than that of the B component. The higher within-site average angular dispersion for the C component ($\sim 13^\circ$) compares well with Late Triassic secular variation estimates of Irving and Pullaiah (1976), suggesting a detrital or rapidly acquired chemical remanent magnetization, whereas the comparatively lower average within-site angular dispersion ($\sim 8^\circ$) of the B component is consistent with the interpretation that the B component represents a remagnetization acquired over a relatively longer time interval. Further evidence for an early acquisition of the C component is the 40-km, along-strike continuity of magnetic polarity stratigraphy.

The mean tilt-corrected C component paleopole ($53.5^\circ N/101.6^\circ E$) compares well with North American APWP's at about 225 Ma where there is relatively little controversy (for example, Irving and Irving, 1982; Gordon and others, 1984), and thus with many individual Middle to Late Triassic North American reference paleopoles such as from the Carnian-

Norian Popo Agie Formation ($56^\circ N$, $96^\circ E$) of Wyoming (Grubbs and Van der Voo, 1976; Pipirinos and O'Sullivan, 1978). Uncertainty in age assignments, combined with the possibility of Colorado Plateau rotation, could account for the apparent discrepancies between the C component paleopole and the poles from the nominally Late Triassic Chinle Formation sampled both off the Plateau in New Mexico (Reeve and Helsley, 1972) and on the Plateau in Utah (Reeve, 1975). Both Chinle poles fall on a much younger portion of Gordon and others' (1984) APWP than our C component pole. This suggests that both Chinle studies sampled rocks that are either younger or at least magnetized later than the middle Carnian to early Norian rocks sampled here. In fact, according to Gordon and others (1984), the Church Rock Member of the Chinle studied by Reeve (1975) may be as young as Early Jurassic due to the uncertainties of correlation within the Triassic/Jurassic stratigraphy of the southwest.

Although the B component is most probably secondary, acquired sometime after deposition of the sediments and acquisition of the C component, the magnetization is difficult to interpret because, in the absence of a fold test, it is not clear whether the B component was acquired before or after structural tilting, the history of which is itself poorly understood. The present structural dip of sediments of the eastern North America rift basins, such as the Newark, may have even been acquired progressively throughout the interval after their deposition and before cessation of subsidence along the presumably listric border faults of the half grabens in the Middle Jurassic (Manspeizer and Cousminer, 1988). Unfortunately, the B component pole without tilt correction ($72.7^\circ N/89.8^\circ E$) turns out to be most consistent with the Jurassic portion of the APWP of Irving and Irving (1982), whereas the tilt-corrected B component pole ($67.6^\circ N/106.9^\circ E$) corresponds to the Jurassic portion of the APWP of Gordon and others (1984) (Fig. 6). The uncertainty in establishing the age of the B component magnetization relative to the poorly constrained age of the tilting does not allow us to discriminate between the two models for APW.

This uncertainty may extend to the Newark trend igneous N2 pole of Smith and Noltimier (1979), one of the key Jurassic paleopoles in the APWP synthesis of Gordon and others (1984). The N2 paleopole consists of results from dikes and sills in Pennsylvania, New Jersey, and Connecticut variously taken as tilt corrected or uncorrected. About half the VGP's incorporated into the calculation of N2 are results obtained by Beck (1972) from the Newark and Gettysburg

Basins (in bedding coordinates) and used with the tacit assumption that the magnetization was acquired before tilting, although there is no reported explicit field evidence to support this. The tilt-corrected B paleopole falls within 6° of Beck's (1972) tilt-corrected pole ($63.5^\circ N/103.3^\circ E$) from these intrusions; however, the uncorrected B component paleopole and Beck's (1972) results recalculated into the geographic coordinates ($72.8^\circ N/66.0^\circ E$) similarly fall within 7° of one another (Fig. 6).

The close correspondence in direction and polarity between the B and N2 magnetizations (whether tilt-corrected or not) leads us to believe that the secondary B component was acquired at about the same time as the N2 magnetization. Sutter (1988), in his analysis of the radiometric ages of igneous rocks of the early Mesozoic basins of the eastern United States, suggested that two events, an ~ 200 Ma primary crystallization event and an ~ 175 Ma hydrothermal event, were important in the thermo-chemical history of the intrusions. Perhaps the secondary B component resulted from the same thermal or hydrothermal event that gave rise to the N2 paleopole at about 175 Ma. Thus it is possible that the N2 igneous magnetizations are also of secondary origin, as was originally suggested by Smith and Noltimier (1979), and therefore not necessarily pre-tilting. It is interesting that we find no overprints in the sediments corresponding to the N1 pole of Smith and Noltimier (1979), suggesting that although there was considerable igneous activity at N1 time, the N2 event was more effective at remagnetizing the sediments.

In light of the uncertainty in the age of the B component magnetization (or the N2 magnetization) relative to the tilting of the basin, it would be useful to compare the Newark results to other Jurassic paleopoles. The excursion of the Irving and Irving (1982) APWP to high latitudes in the Jurassic, which would tend to support the uncorrected B component pole, is due mainly to the inclusion of the pole from the diabase dike of Anticosti Island, Quebec ($75.7^\circ N/84.7^\circ E$) (Laroche, 1971) and the pole from the White Mountain intrusions of the northeast United States ($85.5^\circ N/126.5^\circ E$) (Opdyke and Wensink, 1966). Although both of these poles have severe shortcomings, as noted by May and Butler (1986), and were not used in their compilation or that of Gordon and others (1984), more recent results from the Moat Volcanics in the White Mountains (Van Fossen and others, 1989) tend to support the high-latitude Jurassic APWP excursion.

On the other hand, the pre-folding interpretation of our B component pole is supported by

two Middle Jurassic paleopoles from the southwestern United States. The Corral Canyon pole (61.8°N, 116.0°E) from southern Arizona, with an assigned radiometric age of 172 m.y. (May and others, 1986), lies within 7° of the tilt-corrected B component paleopole (Fig. 6). The significance of this comparison, however, depends on the thermal, chemical, and tectonic stability of the area in which the Corral Canyon rocks were sampled. As an indication of the possible problems with this paleopole, Hagstrum and Sawyer (1987) found paleomagnetic evidence for local rotations from Cretaceous rocks in the Silver Bell Mountains 125 km northwest of the Corral Canyon site. Our tilt-corrected B component is also virtually coincident with Steiner's (1978) pole (67.5°N, 110.6°E) from the Summerville Formation of eastern Utah, regarded as late Callovian (~164 Ma) (Pipiringos and O'Sullivan, 1978). The Summerville pole is used by Irving and Irving (1982) and Gordon and others (1984) but was rejected by May and Butler (1986) for APWP construction on the grounds that uncontaminated magnetizations were not isolated from a sufficient number of samples.

CONCLUSIONS

Although extensive thermal demagnetization is necessary, two components of magnetization can be isolated from the middle to late Carnian and early Norian sediments of the Newark Basin. In these, the lowermost strata of the Newark Basin, a high unblocking temperature magnetization of normal and reversed polarity, acquired at about the time of deposition of the sediments, produces a paleopole (53.5°N/101.6°E) consistent with the age of the sediments and a correlatable magnetic polarity stratigraphy.

In addition to the high unblocking temperature magnetization, an intense secondary magnetization with a lower unblocking temperature range is also observed. Based on admittedly indirect evidence, the B component was most probably acquired in the Middle Jurassic, at about the same time as an ~175 Ma hydrothermal event inferred from radiometric age data, and contemporaneously with the Newark trend igneous N2 magnetization. Because the relative ages of the tilting and the B component or N2 magnetizations are unknown, no conclusions can be made regarding the two models of North American apparent polar wander (Irving and Irving, 1984; or Gordon and others, 1986; and May and Butler, 1986) based upon these poles. The tilt-corrected B component paleopole (67.6°N/106.9°E) lends support to the general shape of the APWP of Gordon and others (1984), whereas the uncorrected B com-

ponent paleopole (72.7°N, 89.8°E) argues for the Middle Jurassic high-latitude loop in the Irving and Irving (1982) APWP.

The C and B components probably bracket the expected age range of magnetizations in the Newark Basins associated with basin development; C from some of the oldest rocks (middle Carnian) and B recording an ~175 Ma hydrothermal or chemical event. We see no evidence for earliest Jurassic overprints associated with the Newark Basin extrusive event, or consistent and stable post-Jurassic overprints; our success here in isolating a near-syn depositional remanence from these sediments suggests that the later Norian and Early Jurassic age sediments of the Newark Supergroup may record paleomagnetic data relevant to refining the North American APWP.

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