Magnetostratigraphy and paleomagnetic poles from Late Triassic–earliest Jurassic strata of the Newark basin

WILLIAM K. WITTE
DENNIS V. KENT
PAUL E. OLSEN
Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964

ABSTRACT

The Newark basin contains a 7-km-thick sedimentary section, which spans approximately 25 m.y. of the Late Triassic and earliest Jurassic (middle Carnian to Hettangian). Previously paleomagnetic study of the Newark red beds has demonstrated that complete progressive thermal demagnetization can effectively isolate a high-temperature characteristic magnetization. In the lower Newark strata (middle Carnian to early Norian in age), this magnetization yielded a pole position at 54°N, 102°E, and in the upper Newark strata (Hettangian in age) a pole position at 55°N, 95°E. Results from 23 new sites in the middle and upper Norian red beds of the Passaic Formation, including 15 sites from the Jacksonwald region that yield a positive fold test, fill the temporal gap between our two prior studies and yield a pole position at 56°N, 95°E (A_{95} = 4.4°). These results from the middle Newark confirm that North American apparent polar wander was very slow (~0.2°/m.y.) during the Late Triassic through earliest Jurassic.

These new sites define reversed and normal polarity magnetozones that are stratigraphically consistent with and extend our previous results. The Newark reversed and normal polarity characteristic magnetizations form a correlatable pattern of 12 magnetozones that are stratigraphically coherent throughout the basin with respect to independent lithostratigraphic marker units that reflect synchronous, basinwide variations in water depth. Temporal calibration of the Newark magnetostratigraphy on the basis of biostratigraphy, radiometric age determinations, and Milankovich-driven cyclostratigraphy indicates that geomagnetic polarity was reversed 70% of the time and that the mean polarity duration was 2 m.y. or less during the Late Triassic and earliest Jurassic.

INTRODUCTION

During the nascent stages of the breakup of Pangea in the Triassic, half grabens developed in the extended continental crust along the Atlantic coast of North America. The Newark basin, one of the best exposed and certainly the best known of the 10 or so of these eastern North American Mesozoic sedimentary basins, contains an ~7-km-thick lacustrine and fluvial section that spans at least 25 m.y. of the Late Triassic (middle Carnian) and earliest Jurassic (Hettangian) (Figs. 1a and 1b). This thick sedimentary section is apparently complete, without significant hiatuses or unconformities, and includes a lithologic sequence of lake-level cycles that can be traced throughout most of the basin. These lake-level cycles provide independent stratigraphic correlation and potentially a high-resolution, temporal cyclostratigraphic calibration (Olsen, 1986).

Presently the geomagnetic polarity time scale (GPTS) effectively extends back only as far as the Middle Jurassic (Kent and Gradstein, 1986), for times when there is oceanic crust with an interpretable magnetic anomaly record. Attempts to construct a reliable GPTS for earlier periods, such as the Triassic, require thick continuous sections of long duration, without significant hiatuses, and with favorable magnetic properties. The Newark basin sedimentary section is a prime candidate for a geomagnetic polarity reference sequence, which would be useful for correlation within the Newark Supergroup basins as well as globally, especially between marine and nonmarine sections which typically do not share the same biostratigraphic control.

Early paleomagnetic studies of Newark Supergroup and associated rocks concentrated mainly on lavas and associated igneous intrusions and indicated that the rocks carried a predominantly normal polarity magnetization (Dubois and others, 1957; Opdyke, 1961; Irving and Banks, 1961; Bowker, 1960; Beck, 1965, 1972). These results led to the notion of a long normal polarity "superchron" during the Late Triassic and perhaps the Early Jurassic (for example, the Graham interval of McElhinny and Burek, 1971; the Newark interval of Pechersky and Khramov, 1973; and the TRN interval of Irving and Pulliah, 1976). This interpretation has been eroded by the observation that although the Newark Supergroup sediments are now recognized to represent a long interval of time (Cornet and Olsen, 1985), the igneous lavas and intrusions associated with the Newark Supergroup and most heavily sampled for paleomagnetic study (Smith and Noltimier, 1979) were crystallized during a short igneous episode in the earliest Jurassic (~200 Ma; Sutter, 1988; Olsen and Fedosh, 1988), rather than over a prolonged period, such as from 170 to 204 Ma as suggested, for example, in the Irving and Irving (1982) paleomagnetic pole compilation.

Reversely magnetized sediments from the Newark basin were noted by Bowker (1960), although the study of McIntosh and others (1985) presented the first comprehensive stratigraphic sampling of a large interval of the Newark section and resulted in a broadly correlative magnetostratigraphy for the basin. In that study, 94% of the sample polarity determinations were made on the basis of a blanket demagnetization to 550 °C, the balance of the determinations based on demagnetization to 450, 610, or 650 °C. Examination of the six Zijderveld (1967) demagnetograms presented in that paper reveals that thermal treatment to 550 °C is usually not adequate to unambiguously determine the polarity of the high-temperature characteristic magnetization. Incomplete removal of a normal polarity overprint by a blanket thermal demagnetization to 550 °C can perhaps account for the many stratigraphic levels of apparently mixed polarity in that seminal study.

We have found that complete progressive thermal demagnetization of all samples to 680 °C, the Curie point of hematite, is necessary and

Geological Society of America Bulletin, v. 103, p. 1648–1662, 9 figs., 2 tables, December 1991.

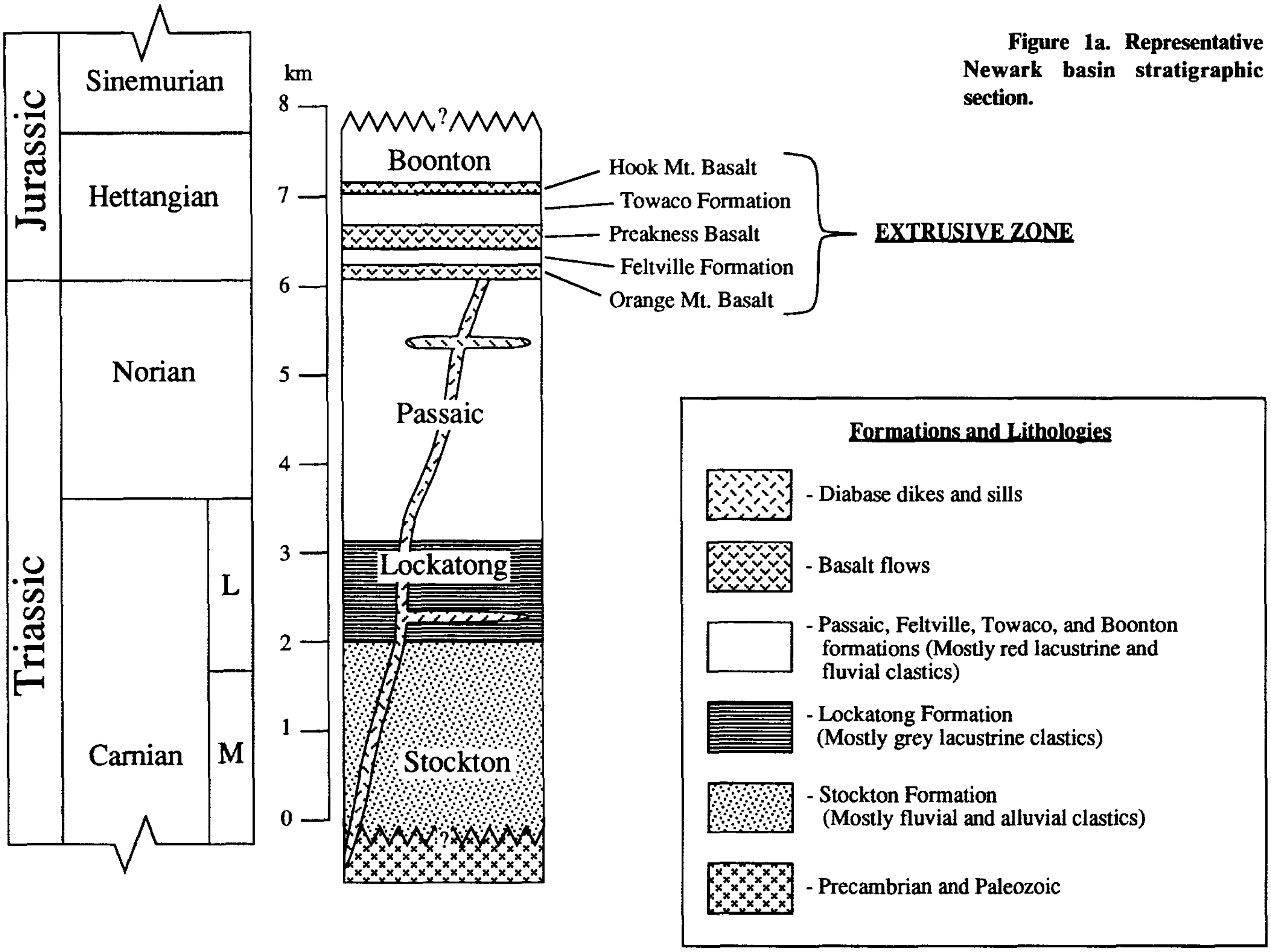


Figure 1a. Representative Newark basin stratigraphic section.

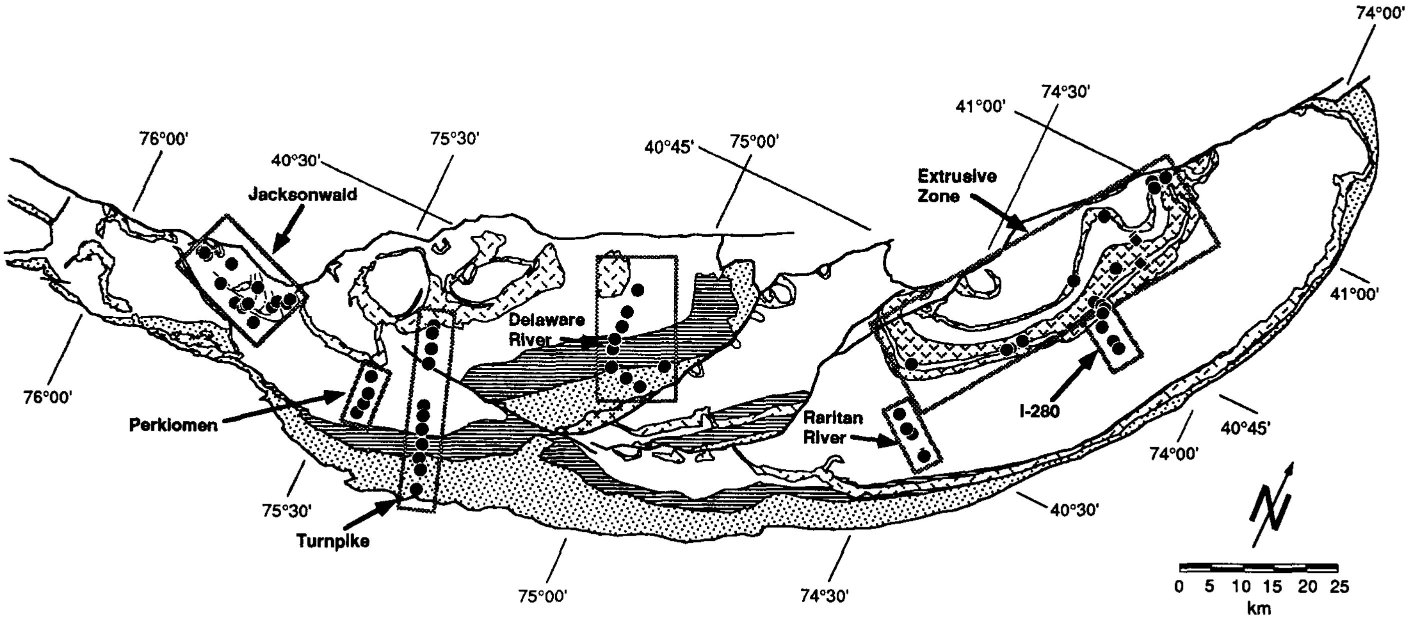


Figure 1b. Geologic sketch map of the Newark basin (Olsen and others, 1989), showing the locations of outcrop sites (circles) and borehole sites (diamonds). Key to formations as in Figure 1a.

TABLE 1. SITE-MEAN CHARACTERISTIC (C COMPONENT) MAGNETIZATION DIRECTIONS FOR THE UPPER PASSAIC FORMATION

Site	n/Type	Lat (N)	Lon (W)	Strike	Dip	k	α_{95}	Geo		Bed	
								Dec	Inc	Dec	Inc
Raritan River section											
TGA	5/I	40°30.53′	74°28.39′	228	12N	22	16.6	003.6	19.0	001.4	10.6
TGC	4/I	40°30.77′	74°29.22′	228	11N	34	15.9	026.3	35.0	019.9	30.4
TGD	5/I	40°29.19′	74°26.03′	230	10N	32	13.7	005.3	20.1	003.1	13.0
TGE	5/I	40°29.25′	74°26.14′	218	13W	17	19.4	010.3	27.9	005.1	21.4
TGF	2/II	40°29.28′	74°26.24′	236	16N	52	—	194.3	-30.0	189.1	-18.6
TGJ	8/I	40°30.78′	74°31.70′	230	13N	12	16.6	000.8	20.5	358.8	10.6
Jacksonwald section											
TJA	4/I	40°18.81′	75°50.67′	278	74N	13	26.3	021.3	65.8	013.5	-07.7
TJB	4/I	40°16.35′	75°43.91′	238	20N	13	26.3	009.4	37.0	002.5	21.2
TJC	5/I	40°16.10′	75°44.02′	254	25N	32	13.8	017.7	35.8	011.6	14.2
TJD	4/I	40°15.82′	75°44.22′	242	30N	28	17.6	202.0	-42.9	188.9	-20.7
TJE	2/II	40°18.03′	75°43.62′	153	35W	168	—	182.0	15.7	185.7	-02.6
TJF	6/I	40°19.00′	75°47.69′	148	37W	31	12.3	184.3	10.2	183.8	-12.0
TJG	3/I	40°17.01′	75°47.80′	268	28N	127	11.0	196.8	-48.9	191.3	-21.8
TJH	6/I	40°16.02′	75°45.33′	268	28N	246	4.3	025.5	44.7	018.4	18.9
TJI	5/I	40°18.87′	75°51.32′	291	65N	162	6.0	352.8	59.3	006.8	-02.6
TJJ	4/I	40°18.87′	75°51.32′	287	50N	26	18.2	352.9	77.7	011.0	28.6
TJK	0/III	40°18.22′	75°39.68′	293	28N	—	—	—	—	—	—
TJL	2/II	40°18.20′	75°39.27′	293	30N	14	—	177.3	-49.8	185.6	-21.7
TJM	6/I	40°17.92′	75°39.88′	293	20N	31	12.3	345.1	33.8	350.8	17.5
TJN	3/I	40°17.58′	75°40.94′	108	20S	23	26.1	176.2	11.4	176.5	-07.1
TJO	4/I	40°17.50′	75°40.94′	118	27S	44	14.0	172.5	15.8	173.9	-06.4
TJP	4/I	40°17.00′	75°41.22′	118	25S	28	17.8	343.9	-00.2	341.2	17.4
TJQ	5/I	40°15.10′	75°42.21′	268	40N	31	13.9	356.3	53.5	357.2	13.5
TJR	3/I	40°18.87′	75°51.32′	282	56N	28	24.0	313.8	73.6	357.0	25.0
I-280 section											
TGG	3/I	40°45.15′	74°11.44′	231	11N	16	31.9	194.8	08.0	196.5	14.2
TGH	3/I	40°45.48′	74°12.33′	222	7W	14	34.0	199.6	-00.3	199.7	02.4
TGI	4/I	40°46.28′	74°14.18′	239	9N	33	16.3	199.6	-16.2	197.9	-10.3
Upper Passaic mean type I site direction											
All	23/I							006.4	29.7	005.5	13.0
								k = 8 α_{95} = 11.9		k = 30 α_{95} = 5.6	

n, number of samples (sites for overall mean); Type, level of data reliability (criteria discussed in text); Lat, Lon, north latitude and west longitude of site; Strike, Dip, bedding attitude observed at each site; k, α_{95}, best estimate of precision parameter and radius of 95% confidence interval about the mean; Dec, Inc, declination and inclination of mean directions (in degrees), in geographic frame of reference (Geo) and after correction for bedding orientation (Bed).

effective to isolate reversed and normal characteristic magnetizations from the oldest (middle Carnian to early Norian) sedimentary rocks of the Newark basin section (Witte and Kent, 1989) and yields uniform within-site polarities. Higher in the section, results from comprehensive sampling of the earliest Jurassic (Hettangian) extrusive zone sediments of the Newark basin compared to the coeval basalts confirm that the sediments are reliable paleomagnetic recorders (Witte and Kent, 1990). Paleomagnetic pole positions from those two studies of the lower and upper Newark strata show little separation (4° ± 7°) and thus imply a very slow rate of apparent polar wander (APW) over 25 m.y. of the Late Triassic.

The new results presented here from the middle Newark strata, of middle and late Norian age, fill in the gap between our two prior studies and test the hypothesis of slow APW for North America during the Late Triassic. This paper also places our entire collection of polarity data in a time-stratigraphic framework in order to develop a Late Triassic and Early Jurassic GPTS.

GEOLOGIC SETTING AND SAMPLING

The sediments that accumulated in the Newark basin during the middle Carnian through Hettangian consist of predominantly fluvial clastic material near its base (the Stockton Formation) and predominantly lacustrine mudstones with minor fluvial sandstones higher in the section (the Lockatong, Passaic, Feltville, Towaco, and Boonton Formations) (Fig. 1b). The lacustrine clastic rocks are typically red with interbedded gray and black beds, which form a basis for subdivision of some of the sedimentary formations into a large number of members (for example, the Lockatong and Passaic Formations with about 20 members) (Olsen and others, 1989). These laterally persistent members reflect basinwide variations in lake water depth and are thus time horizons useful for correlation (Olsen, 1986; Olsen and others, 1989).

Structurally, the Newark basin is a half graben bounded to the northwest by a series of normal faults and to the southeast by a basal unconformity. The strata generally dip homoclinally to the northwest at about 10°–15° except in the limbs of transverse folds associated with the border fault, such as the Jacksonwald syncline (Fig. 1b). During and after deposition, normal faults dissected the Newark section into several major fault blocks, the later erosion of which provides good, albeit discontinuous, exposure of the entire section along rivers, streams, and highways in several different regions of the basin.

The upper Passaic Formation was sampled at 27 sites in strata of middle and late Norian age (Table 1). As in our previous studies, most of the sites were concentrated along across-strike transects spaced tens of kilometers apart. By sampling in this manner, it was possible to test the reproducibility and lateral continuity of the magnetozones. At each site, 5 or more independently oriented cores (or oriented blocks in rare cases) were taken over a stratigraphic interval of 3 to 30 m. Cores were oriented using a magnetic compass or using a sun compass in cases where anomalous local magnetic declinations were encountered. The sampling strategy was designed to provide temporal coverage within each site for an estimate of the time-averaged field for pole studies; however, the stratigraphic position of each site was always determined with respect to characteristic stratigraphic markers in the basin for magnetostratigraphic purposes. Outcrops are discontinuous in the study area with few very thick stratigraphic exposures; thus our sampling regimen was compatible with outcrop availability. Stratigraphic distances between sites were calculated from bedding strikes and dips and the interpretation of the local structure from geologic maps (Lyttle and Epstein, 1987; Olsen and others, 1989).

Throughout the Newark basin, the Upper Triassic sediments were intruded by diabase dikes and sills (as much as 400 m thick) at ~200 Ma, coeval with the Hettangian igneous extrusive episode (Dunning and Hodych, 1990; Sutter, 1988; Ratcliffe, 1988). These intrusions are in many cases rimmed by hornfelsed sediments, which typically produce uninterpretable demagnetization data; however, these alteration aureoles are at most about 100 m thick. The intrusions themselves are inferred to have been partially or totally remagnetized during the Middle Jurassic (Witte and Kent, 1989); thus they and their hornfelsed rims were avoided in our sampling.

PALEOMAGNETIC RESULTS

Methods

After the core samples were trimmed into 10-cm^3 specimens, their natural remanent magnetization (NRM) was measured on a two-axis ScT

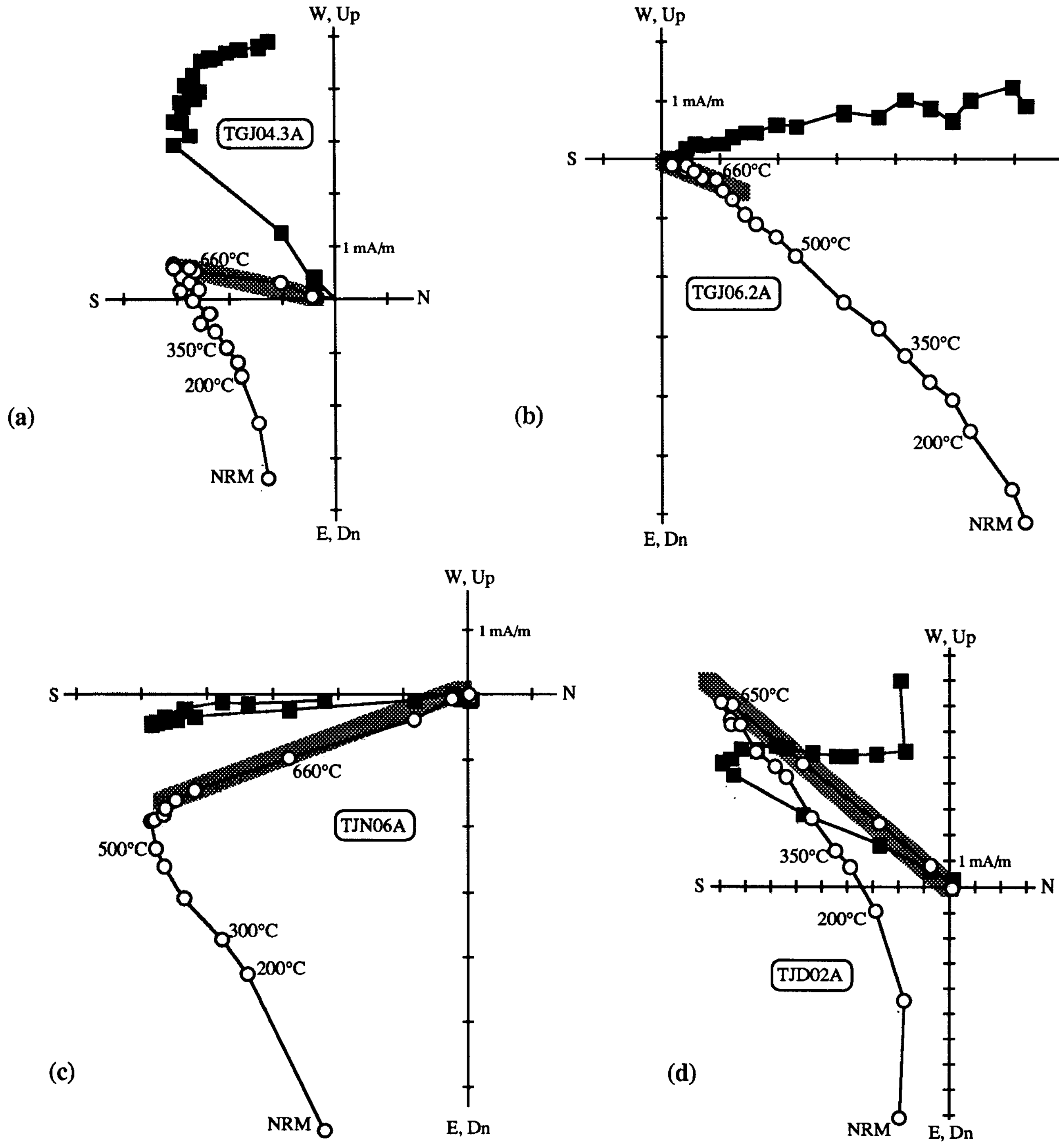
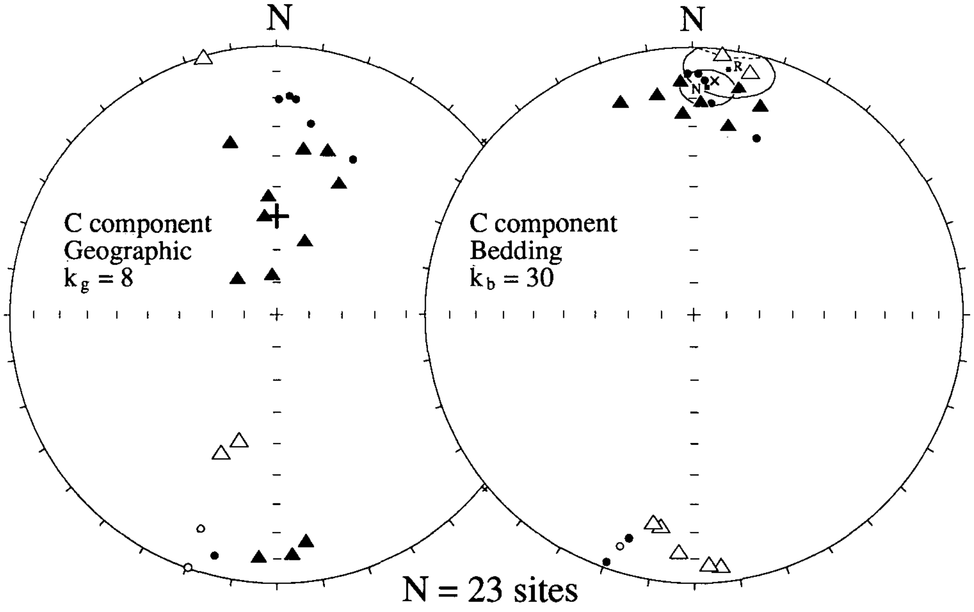


Figure 2. Zijderveld demagnetograms illustrating typical demagnetization behavior observed in Passaic red beds from the Raritan River and Jacksonwald regions of the Newark basin. Closed symbols are projections onto the horizontal plane, open symbols are projections onto the vertical north-south plane, all in geographic coordinates. Stippled bars highlight the characteristic (C component) demagnetization trajectories. (a) Sample taken 4.5 m below, and (b) sample taken 0.1 m below the base of the Ukrainian Village member at site TGJ from Raritan River; (c) sample taken in beds of southwest dip, and (d) sample taken in beds of northwest dip in the Jacksonwald syncline.

Figure 3. Equal-area stereographic projections showing the 23 type I C component site-mean directions for the middle Newark pole before and after bedding corrections. Triangles indicate site directions from the Jacksonwald region, circles from the Raritan and I-280 sections. Solid/open symbols indicate downwardly/upwardly directed site means. Squares (with α_{95} envelopes) indicate the mean directions of 15 sites with normal polarity (N) and 8 sites with reversed polarity (R; the antipode is shown). The mean direction of all 23 sites is indicated by a ×. The + indicates the present dipole field at the sampling sites.



cryogenic magnetometer with a 6-cm access. Alternating-field demagnetization to 100 mT indicated that the NRM of the red beds resides mainly in high-coercivity magnetic minerals. This is confirmed in isothermal remanent magnetization experiments (Witte and Kent, 1989), which suggest that the predominant carrier of the remanent magnetization in these rocks is hematite. Progressive stepwise thermal demagnetization to the maximum unblocking temperature of hematite (~680 °C) has proven effective in decomposing the NRM into characteristic and overprint magnetization components.

Most of the remanence measurements and thermal demagnetization experiments on samples from the Passaic Formation were made in a shielded room, as it became available, with an ambient field of about 300 nT. Stepwise thermal demagnetization at 15 to 20 steps was performed on at least one specimen from each core using either a pass-through Schonstedt demagnetizer (<10 nT during cooling, ~±15 C° temperature control, 9-sample capacity) or, upon completion of its construction, a 3-zone thermal demagnetizer (<5 nT during cooling, ~±5 C° temperature control, 50-sample capacity), which heats and cools the samples in the same chamber. The two thermal demagnetizers yielded nearly identical demagnetization results for companion specimens from the same core. Components of NRM, identified as linear trajectories on Zijderveld demagnetograms, were estimated through principal-component analysis (PCA) (Kirschvink, 1980). Site mean component directions were calculated (Fisher, 1953) from at least three independently oriented cores, each based on complete progressive demagnetization on one or more specimens.

Isolation of Magnetization Components

During the demagnetization of NRM of samples from the Passaic Formation, 2 components of magnetization were typically identified after the removal of spurious magnetizations generally below 200 °C (Fig. 2). An intermediate unblocking temperature component of magnetization, very similar to that isolated in our previous studies of stratigraphically adjacent and lithologically similar red beds (Witte and Kent, 1989, 1990), was isolated between 300 and about 630 °C. This uniformly normal polarity overprint magnetization fails a fold test and is consistently steeper than the characteristic magnetization yet shallower than the Earth's present field at the sampling sites (Witte and Kent, 1991). The age of this magnetization most likely corresponds to that of the hydrothermal disturbance (~175 Ma) that Sutter (1988) suggested reset the K-Ar systems of many of the diabase intrusions (Witte and Kent, 1989). The overprint (B component) magnetization is not of direct interest here and is discussed elsewhere (Witte and Kent, 1991), but it is important to recognize the ubiquitous presence of this secondary magnetization throughout the basin as a possible contaminant that must be isolated from the characteristic (C component) magnetization.

A high-unblocking temperature component of magnetization which demagnetizes to the origin was revealed above about 640 °C in thermal demagnetization experiments (Fig. 2). This C component magnetization was isolated in 3 or more independently oriented samples from a total of 23 middle and late Norian sites and is similar in its demagnetization behavior to the high-unblocking temperature component observed in our earlier Newark studies. In these 23 middle and late Norian sites, which yielded reliable estimates of the C component direction, the magnetization was directed to the north and down (normal polarity) in 15 sites and south and up (reversed polarity) in 8 sites (Fig. 3; Table 1). The overall mean direction (after inverting the directions of reversed polarity sites) for the 23 sites is declination/inclination = 006.4°/29.7° (k = 8, α_{95} = 11.9°) before structural corrections and 005.5°/13.0° (k = 30, α_{95} = 5.6°) after structural corrections are applied (Table 1). The precision parameter is improved by a factor of 3.75 after tilt correction of the 23 site mean directions, indicating a positive fold test (McElhinny, 1964), even though the difference in dispersion is controlled largely by structural variation associated with the 15 sites from the Jacksonwald syncline.

Jacksonwald Syncline Fold Test

Dips in the folds of the Jacksonwald region are generally about 35° but locally range to 70° with fold axes running northwest-southeast and plunging gently (~15°) to the northwest. Folding started very soon after or

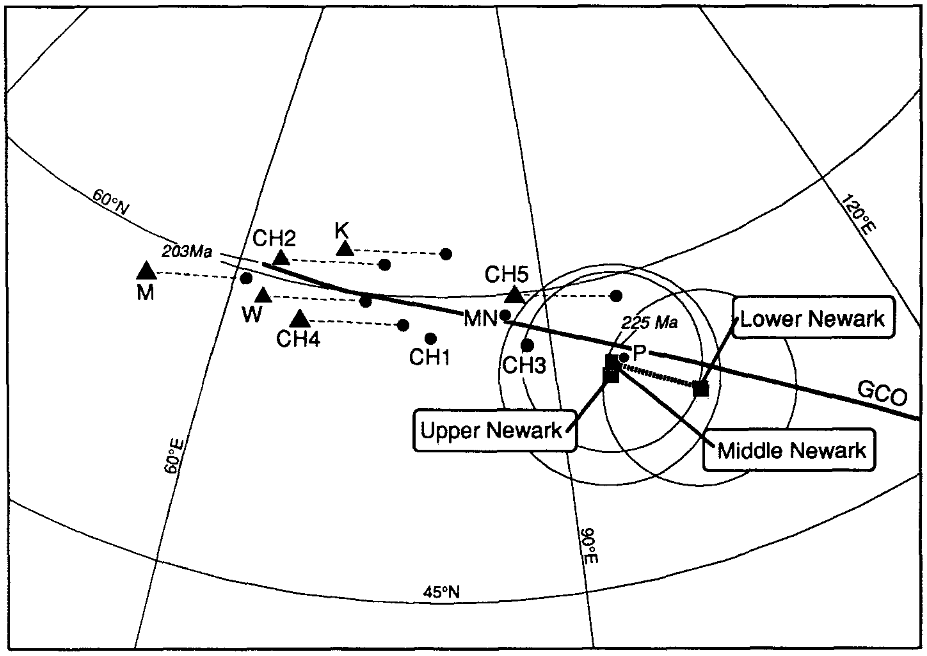


Figure 4. North American Late Triassic through Early Jurassic paleomagnetic reference poles and the APW path of Gordon and others (1984) with their predicted 225 and 203 Ma pole positions. Reference poles used and listed in Gordon and others (1984) include P, Carnian/Norian Popo Agie pole; MN, 215 Ma Manicouagan impact-structure pole; CH1, Late Triassic Chinle (Redonda Member) pole; W, Sinemurian Wingate pole; CH2, Late Triassic Chinle (Church Rock Member) pole; K, Pliensbachian Kayenta Formation pole. Also shown are more recent results from the southwestern United States: CH3, Late Triassic Chinle Formation (Upper Shale Member) pole (Bazard and Butler, 1989); CH4, Late Triassic Chinle Formation (Owl Rock Member) pole (Bazard and Butler, 1990); CH5, Late Triassic Chinle Formation (Shinarump Member) pole (Molina-Garza and others, 1990); M, Sinemurian/Pliensbachian Moenave Formation pole (Ekstrand and Butler, 1989). Triangles/circles indicate the location of the CH2, CH4, CH5, W, M, and K poles before/after correction for 5.0° of Colorado Plateau rotation (Bryan and Gordon, 1990). Squares indicate characteristic magnetization poles from lower Newark strata (middle Carnian/ early Norian; Witte and Kent, 1989), middle Newark strata (middle and late Norian; this paper), and upper Newark strata (Hettangian; Witte and Kent, 1990).

during deposition, as evinced by thickness and facies relations within the cyclic lacustrine sediments, and was probably related to subsidence of the basin along the border fault (Olsen and others, 1989). The geometry of the folds suggests that the plunging and the folding were acquired nearly simultaneously. Folding was certainly completed prior to regional coastal onlap in the Cretaceous.

The C component magnetization directions (after inverting reversed polarity site directions) in the upper Passaic Formation of the Jacksonwald syncline are considerably more coherent after a simple tilt correction (rotation of the beds to horizontal about the present strike) than before (Fig. 3); an incremental bedding correction analysis shows that minimum dispersion is achieved only at practically full (96%, indistinguishable from 100%) tilt correction. For the 15 sites in the Jacksonwald region, the precision parameter is improved by a factor of 5.6 in the bedding frame of reference, which is significant at the 99% confidence level according to the f-ratio criterion of McElhinny (1964), a method judged to be overly stringent by McFadden and Jones (1981). Furthermore, the distribution of site directions is non-Fisherian before tilt correction and becomes indistinguishable from Fisherian after tilt correction (using the χ^2 test of Watson and Irving, 1957). The substantial reduction in dispersion after tilt correction leads us to conclude that the characteristic magnetization was most likely acquired before any significant folding and thus very early in the history of these red beds. Therefore, a tilt correction is necessary to establish the direction of the ancient geomagnetic field.

Reversal Test

The tilt-corrected mean directions from the normal sites (003.8°/15.7°, k = 33, α_{95} = 6.8°, N = 15) and from the reversed sites (188.5°/−7.9°, k = 28, α_{95} = 10.6°, N = 8) differ from antipodality by 9.1° (Fig. 3). This difference is not statistically significant, thus indicating that these directions pass the McFadden and McElhinney (1990) reversal test with a C classification; most of the difference is in inclination (the mean reversed direction is 7.8° shallower than the mean normal direction), which can be attributed to minor overprint contamination. If the contamination is small (as is suggested by the observed small angular departure from antipodality) and independent of polarity, then its directional bias on the overall C component mean should already be largely removed by averaging over the 23 normal and reversed sites. This is confirmed in the observation that the preferred overall mean (005.5°/13.0°, N = 23) differs by only about 1° from the mean of the normal and reversed (inverted) subsets of sites (006.2°/11.8°, N = 2).

Paleomagnetic Poles and Site Paleolatitudes

The 15 sites which form the positive fold test in the Jacksonwald locality, the 5 sites from the Raritan traverse, and the 3 sites from the I-280 traverse yield a total of 23 site mean virtual geomagnetic poles (VGP's), which produce, after tilt correction, a mean middle Newark pole (upper Passaic Formation) at 56°N, 95°E (K = 49, A_{95} = 4°). This middle to late Norian pole does not differ significantly (at 95% confidence level) from the lower Newark pole (middle Carnian/early Norian age) at 54°N, 102°E (A_{95} = 5, N = 19) and nearly coincides with the upper Newark pole (Hettangian age) at 55°N, 95°E (A_{95} = 5, N = 11) from the Newark basin section (Witte and Kent, 1989, 1990) (Fig. 4; Table 2).

The Newark section pole positions imply a near-equatorial paleogeographic location for the Newark basin throughout most of the Late Triassic and earliest Jurassic (Fig. 5). The paleolatitude estimates (4° ± 3°N in the

TABLE 2. CHARACTERISTIC (C COMPONENT) MAGNETIZATION DIRECTIONS AND POLE POSITIONS FOR NEWARK BASIN SEDIMENTARY SECTION

Unit	N	k	α_{95}	Dec	Inc	K	A_{95}	Lat	Lon	Age	Reference
Lower Newark	19	32	6.0	001.8	7.5	50	4.8	54	102	Middle Carnian to early Norian	Witte and Kent, 1989
Middle Newark	23	30	5.6	005.5	13.0	49	4.4	56	95	Middle and late Norian	This paper
Upper Newark	11	59	6.0	006.3	12.9	72	5.4	55	95	Hettangian	Witte and Kent, 1990
Joint mean Newark basin	53	34	3.4	004.3	11.0	53	2.7	55	97	Middle Carnian/ Hettangian	This paper

Unit: Lower Newark consists of results from the Stockton, Lockatong, and lowest Passaic Formations; Middle Newark consists of results from the middle and upper Passaic Formation; Upper Newark consists of results from the extrusive zone sediments. N, number of sites that contribute to mean direction; k, α_{95}, best estimate of precision parameter and radius of 95% confidence interval about the mean direction; Dec, Inc, tilt-corrected declination and inclination of mean directions in degrees; K, A_{95}, best estimate of precision parameter and radius of 95% confidence interval about the mean pole; Lat, Lon, north latitude and east longitude of mean of the site VGP's; Age, age of unit.

middle Carnian/early Norian, 7° ± 3°N in the middle to late Norian, and 6° ± 3°N in the Hettangian) are consistent with a tropical climate interpreted from the Newark paleontology and lithology (Van Houten, 1977; Cornet and Olsen, 1985; Olsen and Sues, 1986).

POLARITY DATA AND THEIR STRATIGRAPHIC CONTEXT

Reliability and Site Classification

The majority of the sites yielded NRM demagnetograms with a linear C component decay to the origin in at least three independently oriented specimens. This type of site behavior we call type I and deem suitable for paleopole and magnetostratigraphic studies. A small group of sites yielded a linear trajectory estimate of the C component of magnetization direction in less than three independently oriented samples, owing to an especially predominant overprint or owing to spurious magnetizations acquired during the final high-temperature demagnetization steps. This level of site reliability we term type II; we included data of this type in our polarity compilation but did not use these sites in the pole calculation. Sites from which we could not even establish the polarity of the high-unblocking temperature component in any specimens were relegated to type III and were rejected from both magnetostratigraphic and paleopole analyses.

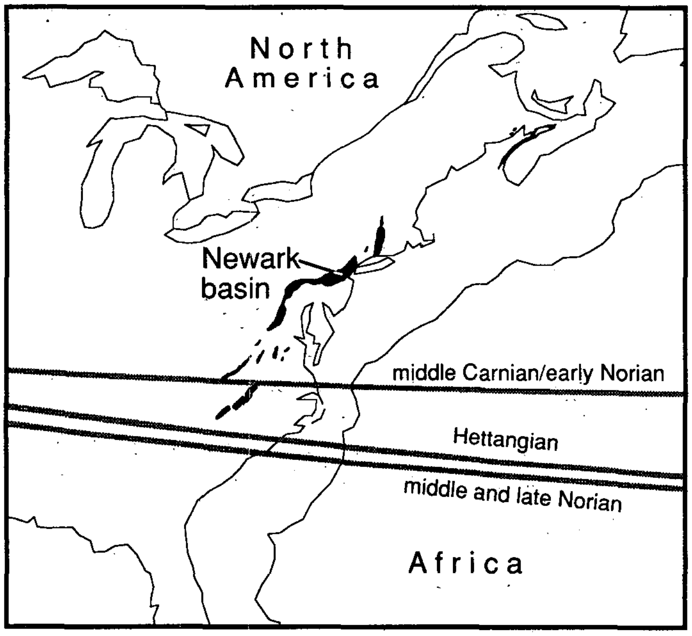


Figure 5. Late Triassic and earliest Jurassic paleogeographic reconstruction of North America and Africa (Klitgord and Schouten, 1986) with the outlines of the Newark and other Mesozoic eastern North American rift basins shown in black. The three stippled curves indicate the positions of the paleoequator corresponding to the lower Newark (middle Carnian/early Norian), middle Newark (middle and late Norian), and upper Newark (Hettangian) paleopoles.

As noted above, the 27 upper Passaic Formation sites yielded 23 type I results. Of the four sites excluded from the pole calculation, three (TGF, TJE, and TJL) were type II sites and only one (TJK) was a type III result. In the middle Carnian/early Norian study (Witte and Kent, 1989), 24 sites were sampled and 19 can be categorized as type I results. One site (WCA) can be designated as type II and is here included in the magnetostratigraphic synthesis, but four sites (TTA, TTK, TDD, and TDG) yielded no useful pole or polarity information and thus are assigned to type III. In the Hettangian study (Witte and Kent, 1989), 11 of the 13 sedimentary sites sampled can be categorized as type I results. The two sites rejected from the pole calculation (TWA, TFF) did demonstrate normal polarity C components and are included here in the magnetostratigraphic synthesis as type II data. Results from the four ACE boreholes are not used for pole calculation in this paper but are included for magnetostratigraphic control.

The Newark basin red beds we have analyzed with complete stepwise progressive thermal demagnetization have yielded a high proportion of useful sites. Of the 64 sedimentary sites sampled in these 3 studies, 83% yielded reliable data for paleopole determination (53 type I), and 92% yielded what we judge to be reliable magnetostratigraphic information (53 type I plus 6 type II).

Site VGP Relative Latitudes

We have used the mean (north) paleomagnetic pole position derived from the 53 type I site VGP's (55°N, 97°E, A_{95} = 3°), which is very similar to the middle Carnian/early Norian, middle to late Norian, and Hettangian interval pole positions, as a convenient reference for calculating the relative latitude of the VGP for each individual site. The resulting site VGP relative latitudes are a direct indication of data quality in defining polarity; +90° is the result expected from a normal polarity site, –90° is expected from reverse polarity sites.

From the stratigraphic distribution of the type I and II site VGP relative latitudes in the various sections, we have inferred the position of each magnetozone boundary as the midpoint between stratigraphically adjacent sites (or samples in the case of site TGJ) with opposite polarities.

The details of how the seven stratigraphic transects (Pennsylvania Turnpike, Delaware River, Perkiomen Creek, Raritan River, Jacksonwald, I-280, and the Northern New Jersey extrusive zone) were sampled and their lithostratigraphies have been correlated are described in Figure 6.

CORRELATION AND DEVELOPMENT OF COMPOSITE TIME SCALE

Stratigraphic Framework

Many of the distinctive Newark basin lithologic units referred to above and in Figure 6, such as the Graters, Perkasie, Metlars Brook, and Ukrainian Village members, have been shown by Olsen (1986) to represent basinwide water-depth variations of the Newark basin lacustrine system and can be interpreted as isochronous horizons. Ideally, magnetozones are also isochronous, representing the polarity of the geomagnetic field close to the time of deposition, and are potential means of independent temporal correlation within the Newark basin. If both temporal frameworks are valid, then the magnetozone boundaries should occur in a consistent relationship with the lithostratigraphic members throughout the basin.

On the scale of the sampling available, excellent along-strike continuity of magnetozones is observed between traverses that sample the same part of the section. On a relatively gross scale, the polarity of all sites in the Stockton, Lockatong, and lowermost Passaic Formations is reversed and is followed by a normal-reversed-normal sequence in the lower strata of the Passaic Formation in traverses along the Delaware River, Pennsylvania Turnpike, and Perkiomen Creek (Fig. 6a) over an along-strike distance of ~40 km. Additional normal and reversed polarity magnetozones are identified in the middle Passaic Formation (Fig. 6b). The stratigraphically highest reversed polarity magnetizations encountered in the Newark basin were obtained at sites that are 400 and 620 m (TGI and TJF, respectively) below the base of the extrusive zone, levels that are compatible with McIntosh and others' (1985) observation of reversed polarity 217 m below the base of the extrusive zone (their site 26). The extrusive zone sedimentary strata and basalt flows of northern New Jersey, as well as strata of the overlying Boonton Formation, are without exception of normal polarity, consistent with the observations of McIntosh and others (1985) (Fig. 6c).

In addition to these broad-scale observations, the Graters, Perkasie, Metlars Brook, and Ukrainian Village members provide more precise tests of the consistency of the lithostratigraphic and magnetostratigraphic correlations. The base of the Graters member is apparently of reversed polarity as demonstrated by the polarity of sites near the Graters member [TPC (reversed) ~170 m below the base of the Graters, TTC (reversed) ~40 m below the base of the Graters, and TDB (reversed) ~170 m above the base of the Graters]. The polarity of site TDC (normal) ~60 m below the base of the Graters does not necessarily contradict the conclusion that the base of the Graters is in a reversed polarity zone, although because of the midpoint criterion for delineating the magnetozone boundary between sites TDB and TDC, the Delaware River section by itself would indicate a normal polarity magnetozone extending up to the level of the base of the Graters member.

The base of the Perkasie member is closely associated with a normal to reversed magnetozone boundary, as is indicated by the normal polarity sites TGD and TGE ~100 and ~25 m, respectively, below the base of the member, and TGF (reversed) which sampled within 30 m above the base of the Perkasie member in the Raritan transect (Fig. 6b). This result does not contradict the observed polarity of site TPD (normal, ~10 m below the base of the Perkasie) from the Perkiomen transect (Fig. 6a) and at site

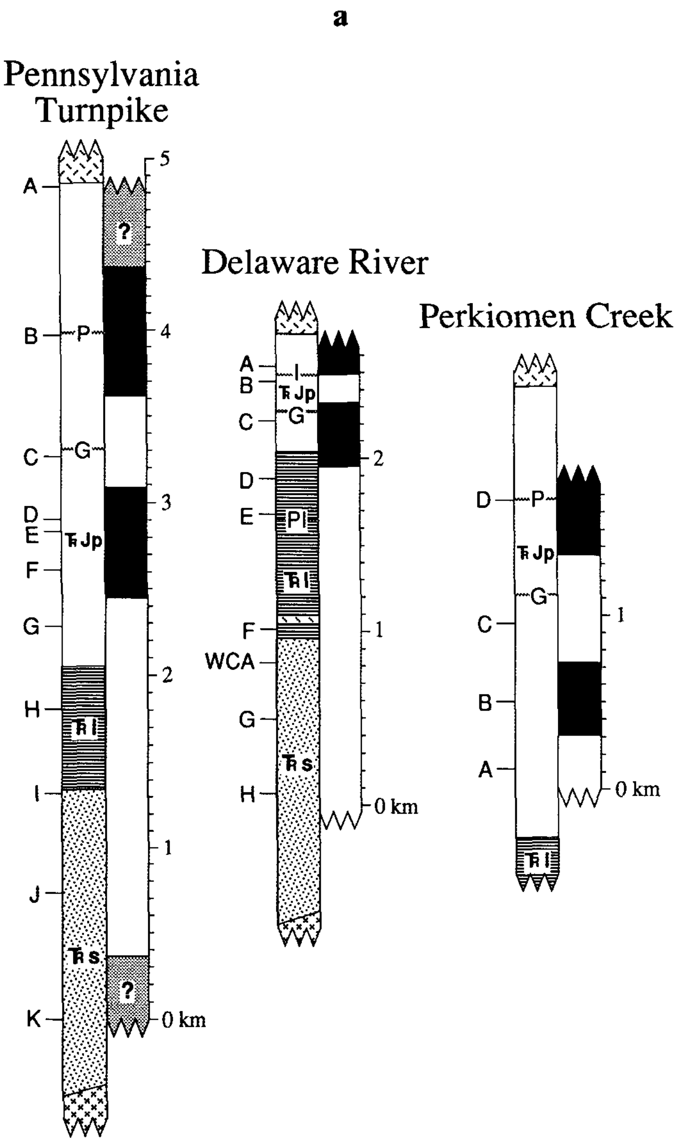


Figure 6. Stratigraphic sections sampled in the Newark basin. Columns at left of each section show stratigraphic units; in ascending stratigraphic order, the formations are Ꞧs, Stockton Formation; Ꞧl, Lockatong Formation; Ꞧ Jp, Passaic Formation; Jo, Orange Mt. Basalt; Jf, Feltville Formation; Jp, Preakness Basalt; Jt, Towaco Formation; Jh, Hook Mt. Basalt; Jb, Boonton Formation. Lithologic marker beds used for correlation and time-scale calibration (Olsen and others, 1989): PI, base of the Prahls Island member; G, base of the Graters member; I, base of member I; P, base of the Perkasie member; MB, base of the Metlars Brook member; 2P, the base of the Second Precinct member (occurs ~50 m below the base of the Ukrainian Village member); U, base of the Ukrainian Village member. (Note: not all members are identified in all sections owing to the nature of the outcrop.) In the right column of each section, the interpreted magnetic polarity is indicated by black for normal polarity and white for reversed polarity, with the queried zones indicating where samples were taken but polarity was not established.

(a) Magnetostratigraphy of the Pennsylvania Turnpike (TT sites), Delaware River (TD sites), and Perkiomen Creek (TP sites) sections (Witte and Kent, 1989).

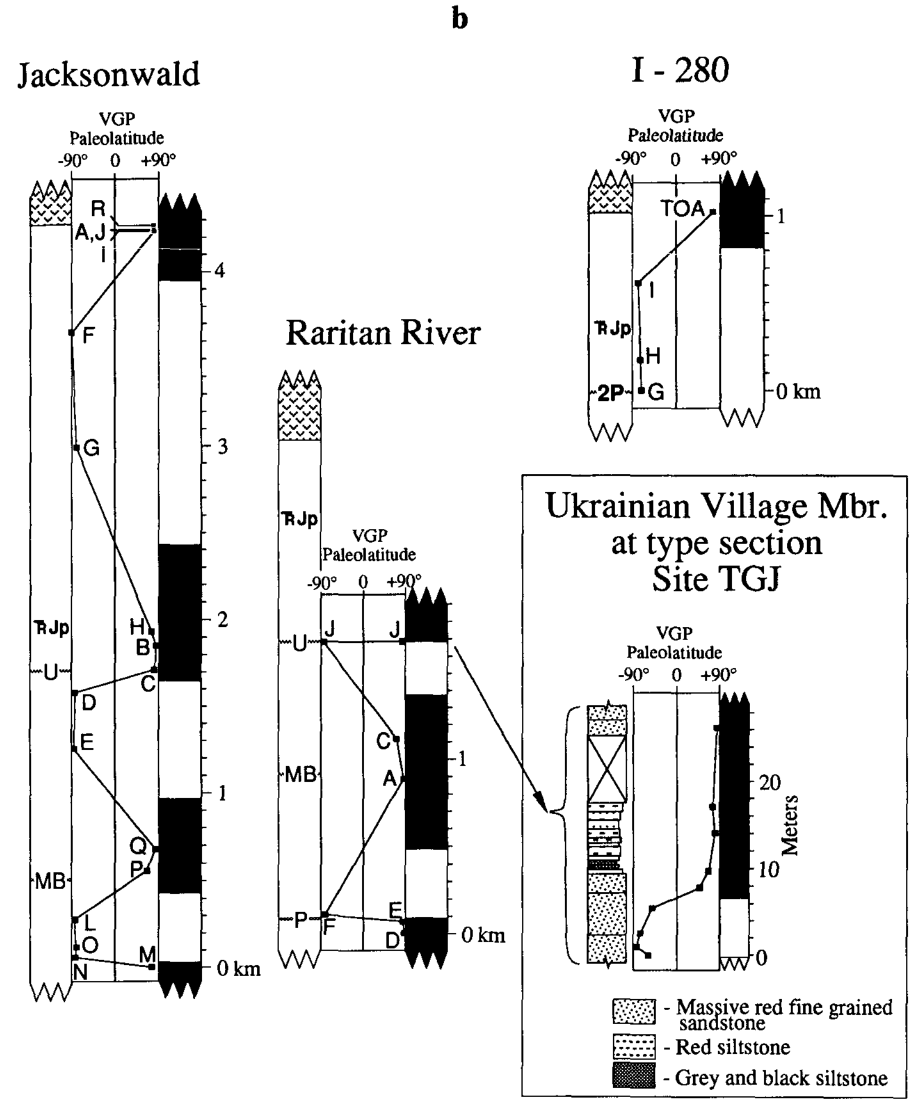
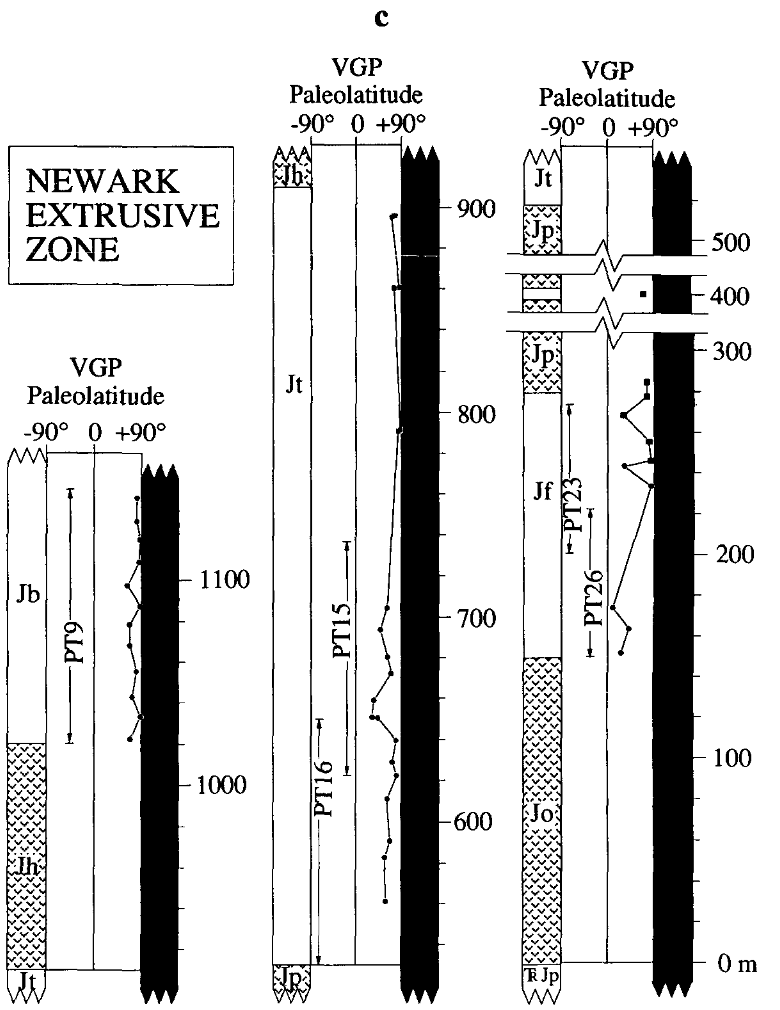


Figure 6. (*Continued*) (b) Magnetostratigraphy of the Jacksonwald (TJ sites), Raritan River (TG sites), and I-280 (TG sites) sections. In the center column, the paleolatitudes of the type I and II site VGP's are plotted (referenced to a mean pole at 55°N, 97°E) as a function of stratigraphic thickness. The inset shows the details of the magnetostratigraphy at the type section of the Ukrainian Village member (site TGJ), with the VGP paleolatitude of individual samples plotted in the center column.



(c) Magnetostratigraphy of the Newark basin extrusive zone and younger sedimentary section. Shown are results from 13 outcrop sites (11 type I and 2 type II) and 19 independently oriented specimens from 4 Army Corps of Engineers (ACE) cores within the extrusive zone sediments (cores PT-26, -23, -16, -15) from Witte and Kent (1990), as well as new results from 12 independently oriented specimens from ACE core PT-9 that sampled the lower 120 m of the Boonton Formation. The center column shows VGP paleolatitudes (referenced to 55°N, 97°E) derived from single borehole specimens (circles) or from site mean directions (squares). Previous work (for example, McIntosh and others, 1985) shows that the Orange Mountain, Preakness, and Hook Mt. basalts are all of normal polarity.

TTB (normal, ~10 m below the base of the Perkasie) from the Pennsylvania Turnpike transect (Fig. 6a). Site TGF was designated a type II site owing to spurious directions attributable to chemical alteration at very high demagnetization temperatures. In spite of these difficulties, the polarity of samples from TGF (reversed) was unambiguous. The polarities of these sites (TGD, TGE, TGF) are apparently consistent with the results of McIntosh and others (1985) from the same outcrop (their locality 17). Their interpretation of the gray beds at this locality as "G/H?" (using McLaughlin's designation, which is recognized as equivalent to the base of the Graters member using the nomenclature of Olsen and others, 1989), however, should be revised, on the basis of the lithologic character of the gray beds, to the base of the Perkasie member.

The Metlars Brook member is dominated by normal polarity as indicated by site TGA (normal, ~30 m below the base of the Metlars Brook member) and TGC (normal, ~200 m above the base of the Metlars Brook member) from the Raritan traverse (Fig. 6b), as well as sites TJP (normal) and TJQ (normal), ~50 and ~120 m, respectively, above the base of the Metlars Brook member in the Jacksonwald region (Fig. 6b).

The closest lithostratigraphic control on any magnetozone boundary presently comes from site TGJ, where samples over a 24-m section document a reversed to normal magnetozone boundary within 3 m below the lowest gray beds of the Ukrainian Village member at the type section in the Raritan River transect (Fig. 6b). This close association of the base of the type section Ukrainian Village member with a reversed to normal magnetozone boundary is consistent with the polarity of sites TJD (reversed) and TJC (normal) which bracket, within 10 m, the base of the Ukrainian Village member in the Jacksonwald syncline (Fig. 6b), some 90 km from the Raritan River section.

In summary, we find consistency in the stratigraphic relationships between polarity magnetozone boundaries and key lithostratigraphic units throughout the Newark basin. This finding supports our earlier conclusion, based on the positive fold test, that the C component magnetization was acquired early in the history of these red beds.

Temporal Framework

The internal consistency between the lithostratigraphic and magnetostratigraphic units of the Newark basin provides a necessary basis to bring these time horizons into a calibrated temporal framework using biostratigraphic, radiometric, and cyclostratigraphic methods. Owing to the lack of marine fossils in the Newark Supergroup, palynology presently provides the most useful biostratigraphic control for the supergroup.

Throughout the Newark basin, the Triassic/Jurassic boundary is placed just below the extrusive zone, within the uppermost 30 m of the Passaic Formation. The boundary is placed between the Manassas–upper Passaic and the *Corollina-meyeriana* palynofloral zones (Cornet, 1977) and is supported by the vertebrate fossil evidence (Cornet and Olsen, 1985). The igneous rocks of the Newark basin yield radiometric ages consistent with these biostratigraphic constraints. Although the igneous intrusions and extrusions were previously thought to have been emplaced during separate igneous episodes spanning at least 20 m.y., recent geologic, geochemical, and geophysical studies have indicated that the Palisades sill actually fed some of the basalt flows of the Newark basin extrusive zone (Ratcliffe, 1988; Kodama, 1983), which is biostratigraphically dated as lowest Hettangian (Cornet and Olsen, 1985). On the basis of $^{40}Ar/^{39}Ar$ dates from recrystallized xenoliths of the Mesozoic country rock included in the Palisades intrusion, Sutter (1988) has concluded that the best estimate for the age of the intrusion and the coeval basalts is 202 Ma. Likewise, U/Pb zircon and baddeleyite ages from the Palisades sill yield an age of about 201 ± 1 Ma (Dunning and Hodych, 1990). These radiometric ages for the Newark igneous event are compatible, within their uncertainties, with the numerical age of the Triassic/Jurassic boundary in recent geologic time scales (for example, 200 ± 5 Ma in Webb, 1981; 213 ± 14 Ma in Harland and others, 1982; 208 ± 18 Ma in Palmer, 1983; and 208 ± 8 Ma in Harland and others, 1990).

The oldest palynoflora recognized in the Newark basin, the New Oxford–Lockatong, is found in the Lockatong Formation and is of late Carnian age (Cornet and Olsen, 1985), although the underlying Stockton Formation most probably extends into the middle Carnian (Olsen, 1986; Schlische and Olsen, 1990), or nominally to at least 225 Ma (Webb, 1981). Thus the duration of Newark sedimentation in the Triassic is about 25 m.y. If a generalized stratigraphic thickness of the Triassic sediments in the basin of about 6,000 m is used, then this implies that the average net sediment accumulation rate was on the order of 240 m/m.y.

A more precise temporal framework for the magnetostratigraphic section is available in the Newark section. The basinwide variations in lake level recorded in the lithostratigraphy are thought to be driven by Milankovitch climate cycles with periods of nominally 20, 100, and 400 ka (Van Houten, 1962, 1964). The lithologic fabrics associated with these cycles have been described throughout a large portion of the Newark sedimentary section (Olsen, 1986), and a high-resolution sedimentation rate model for the basin (Schlische and Olsen, 1990) allows the sedimentary section to be put into calibrated temporal framework.

To calibrate the magnetostratigraphy in terms of the cyclostratigraphic framework, the stratigraphic positions of the magnetozone boundaries have been linearly adjusted relative to major lithostratigraphic markers (the bases of the Lockatong Formation, Prahls Island member, Passaic Formation, Graters member, member I, Perkasie member, Metlars Brook member, Second Precinct member, Ukrainian Village member, and the extrusive zone) as these lithostratigraphic units have been fit to the cyclostratigraphic framework (Olsen, 1986). With the base of the extrusive zone assigned the age of 201 Ma based on the recent Newark radiometric ages (Dunning and Hodych, 1990), the result is a time-calibrated composite magnetostratigraphic polarity section for the Newark basin (Fig. 7).

For the purposes of discussion, the polarity zones identified on the Newark composite polarity section have been assigned lower-case letters from the bottom of the section to the top, with plus or minus superscripts to indicate the predominant polarity (normal or reversed) of each interval. If shorter polarity zones are discovered within these zones, the new zones can be given numerical suffixes that indicate their positions within the larger zones. For example, the Newark k^- zone can be subdivided, from bottom to top, into the Newark $k1^-$, $k2^+$, $k3^-$ subzones if a normal polarity magnetozone is eventually found within this zone. The advantage of this system, similar to the nomenclature of Alvarez and others (1977), is that the larger zones can be subdivided as new intermediate magnetozones are uncovered without reorganizing the higher-order structure of the nomenclature.

All of the polarity zones identified in the composite section are defined by more than one site in more than one section, except for the Newark f^+ polarity zone, which is defined by a single site (TJM) from the Jacksonwald section (Figs. 6b and 7). This site is located several hundred meters above the Perkasie member in the Jacksonwald section and is thus unlikely to correspond to the Newark d^+ zone. It is more likely that the Newark f^+ zone lies within the unsampled interval of the Raritan section between TGas and TGF.

Sampling and Reversal Statistics

Temporal calibration of the magnetozones within the cyclostratigraphic framework allows the reversal rate to be examined on the basis of time. The 25 m.y. of composite section of the Triassic that we sampled includes 12 polarity intervals (Fig. 7) and thus yields a nominal mean polarity duration of ~2 m.y. The sampling density in time is nonuniform,

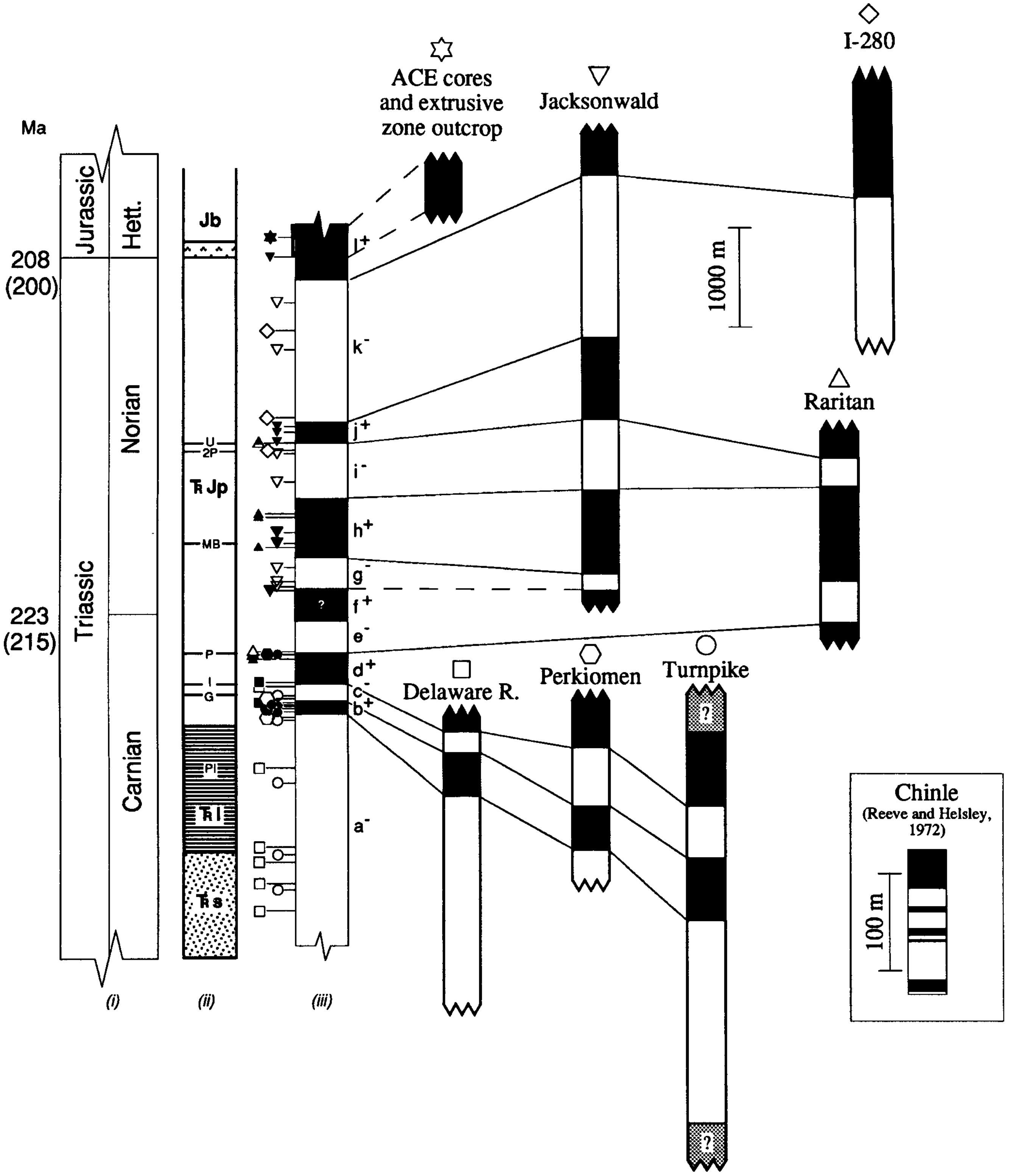


Figure 7. Composite geomagnetic polarity reference sequence derived from the individual stratigraphic thickness sections shown at right and calibrated in time. (i) Late Triassic and earliest Jurassic time scale of Harland and others (1990) with Webb's (1981) numerical ages in parentheses. (ii) Newark basin chronostratigraphy with lithologic tie points (abbreviations as in caption of Fig. 6) (Schlische and Olsen, 1990; Olsen and others, 1989). (iii) Composite polarity sequence adjusted to the Newark basin chronostratigraphy, with Newark polarity zone designations (a^- to l^+). Inset: Chinle Formation magnetostratigraphic section (Reeve and Helsley, 1972) is shown with a 10× vertical exaggeration for comparison with the Newark sections.

however, being largely determined by the availability of outcrop with significant lithologic character to allow positive correlation between sections. The Newark basin site temporal spacings exhibit a skewed distribution with many small spacings and a few very large spacings (Fig. 8); it is likely that this sampling pattern missed some polarity intervals, giving an overestimate of the mean geomagnetic polarity duration (Johnson and McGee, 1983). For example, if only one new polarity subzone was discovered in each of the three large (>2 m.y.) sampling gaps (within the Newark a^- zone, spanning the Newark e^- and f^+ zones, and within the Newark k^- zone), then the number of polarity intervals would increase from 12 to 18 and the mean polarity duration would decrease from 2.1 to 1.4 m.y. Thus, it is best to consider 2 m.y. an upper bound on the mean polarity interval duration.

DISCUSSION

The present results from the upper Passaic Formation combined with our previous work (Witte and Kent, 1989, 1990) provide paleomagnetic data from virtually the entire middle Carnian to Hettangian span of Newark basin sedimentation, with gaps estimated to be no longer than about 2 m.y. The relative ages between the lower, middle, and upper Newark poles are well established on the basis of stratigraphic superposition and continuity. Moreover, the geologic age of the Newark strata is well known biostratigraphically and is supported by $^{40}Ar/^{39}Ar$ and U/Pb radiometric dates. The positive fold test from the upper Passaic Formation and the correlative magnetostratigraphy over the large geographic extent of the basin argue strongly for stability of the characteristic magnetization of the red beds since very nearly the time of deposition. Although the possibility of tectonic rotations within the Newark basin has been suggested (Van Fossen and others, 1986), the evidence for this is equivocal (Kodama, 1987; Van Fossen and others, 1987). The coherence of the paleomagnetic directions from sites in the folds associated with the border fault (for example, the Jacksonwald region) and sites from the homoclinal strata of the central basin (for example, the Raritan River region), however, argues against any significant systematic tectonic rotations within the basin in the vicinity of our sampling.

Paleopoles

Our new middle Newark pole confirms the notion of very slow APW during the Late Triassic to earliest Jurassic, suggested by Witte and Kent (1990) on the basis of the upper and lower Newark poles. Although all three Newark poles fall along the Triassic APW track of Gordon and others (1984), they are not significantly different. The lower and upper Newark poles differ only by 4° ± 7°, implying APW at a rate of ~0.2°/m.y., a virtual stillstand in North American APW for 25 m.y. of the Late Triassic to earliest Jurassic (Fig. 4). Thus the age range of the Newark basin strata apparently does not include the magnetization age giving rise to the 60°N, 60°E cusp in APW postulated by Gordon and others (1984).

The stillstand was apparently followed by more rapid APW in the Early Jurassic. The Sinemurian Moenave pole (60°N, 62°E, after correction for clockwise Colorado Plateau rotation of 5° about a pivot at 37°N, 103°W; Bryan and Gordon, 1990) apparently confirms the 60°N, 60°E cusp in North American APW. The Sinemurian Moenave pole is 18° different from the upper Newark (Hettangian) pole and would demand APW rates of about 3.6°/m.y. (assuming ~5 m.y. from the middle of the Hettangian to the middle of the Sinemurian using the Palmer, 1983, time scale), an order of magnitude more rapid than in the Late Triassic. Recent evidence of a high-latitude paleopole position for North America in the Middle Jurassic (Van Fossen and Kent, 1990) may indicate that rapid APW extended into later parts of the Jurassic as well.

The Chinle Formation of the southwestern United States is biostratigraphically dated as Late Triassic (Pipiringos and O'Sullivan, 1978; Olsen and Sues, 1986; Lucas and Hunt, 1989) and should thus be coeval, at least in part, with the Newark basin section. Whereas the Newark paleomagnetic poles indicate a virtual stillstand in North American APW, however, poles from the Chinle Formation (Reeve and Helsley, 1972; Reeve, 1975; Bazard and Butler, 1989, 1990; Molina-Garza and others, 1990) are widely distributed along Gordon and others' (1984) Triassic North American APW track, from the vicinity of the upper Newark pole to the 60°N, 60°E cusp of Gordon and others (1984) even after correction for Colorado Plateau rotation (Fig. 4). One interpretation of this distribution of Chinle poles is that it represents rapid APW during Chinle deposition; this would imply that the relatively more clustered Newark characteristic magnetizations were acquired nearly simultaneously during a single remagnetization event. Given the Hettangian age of the upper Newark pole strata, this scenario would lead us to expect the Newark poles to plot on a younger part of the APW path than would poles from the Chinle Formation. This is not observed. Instead, the positive fold test in the middle Newark study and the well-constrained age and correlative magnetostratigraphy of the Newark in general lead us to accept the Newark results as reliable Late Triassic and earliest Jurassic poles for North America.

The east-west streaking among the Chinle poles and their overall displacement toward poles from the younger Glen Canyon Group suggest an alternative and more likely explanation for the disparity. The age of the magnetization isolated in the Chinle red beds is not constrained by fold tests or a geographically extensive magnetostratigraphy (Reeve and Helsley, 1972; Reeve, 1975). Thus the reported Chinle directions might represent remagnetizations, and the streaked distribution of the Chinle poles might have been acquired during post-Hettangian (that is, post-Newark) APW at somewhat different times in different geographic regions. This spatiotemporal variability in Chinle remagnetizations could have been controlled by local variation in the uplift, weathering, and erosion which was responsible for the major J0 unconformity that separates the Chinle from the overlying Glen Canyon Group (Pipiringos and O'Sullivan, 1978). In any event, until the reliability of the Chinle magnetizations is demonstrated by definitive field tests, we regard the Newark poles as yielding the more representative estimates of the Late Triassic and earliest Jurassic North American pole positions.

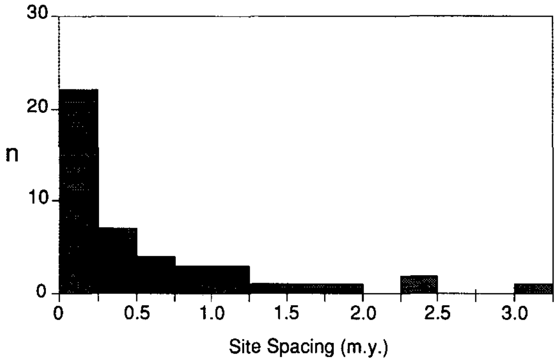


Figure 8. Distribution of Newark type I and II temporal site spacings in Stockton, Lockatong, Passaic, and extrusive zone sediments estimated after cyclostratigraphic time calibration.

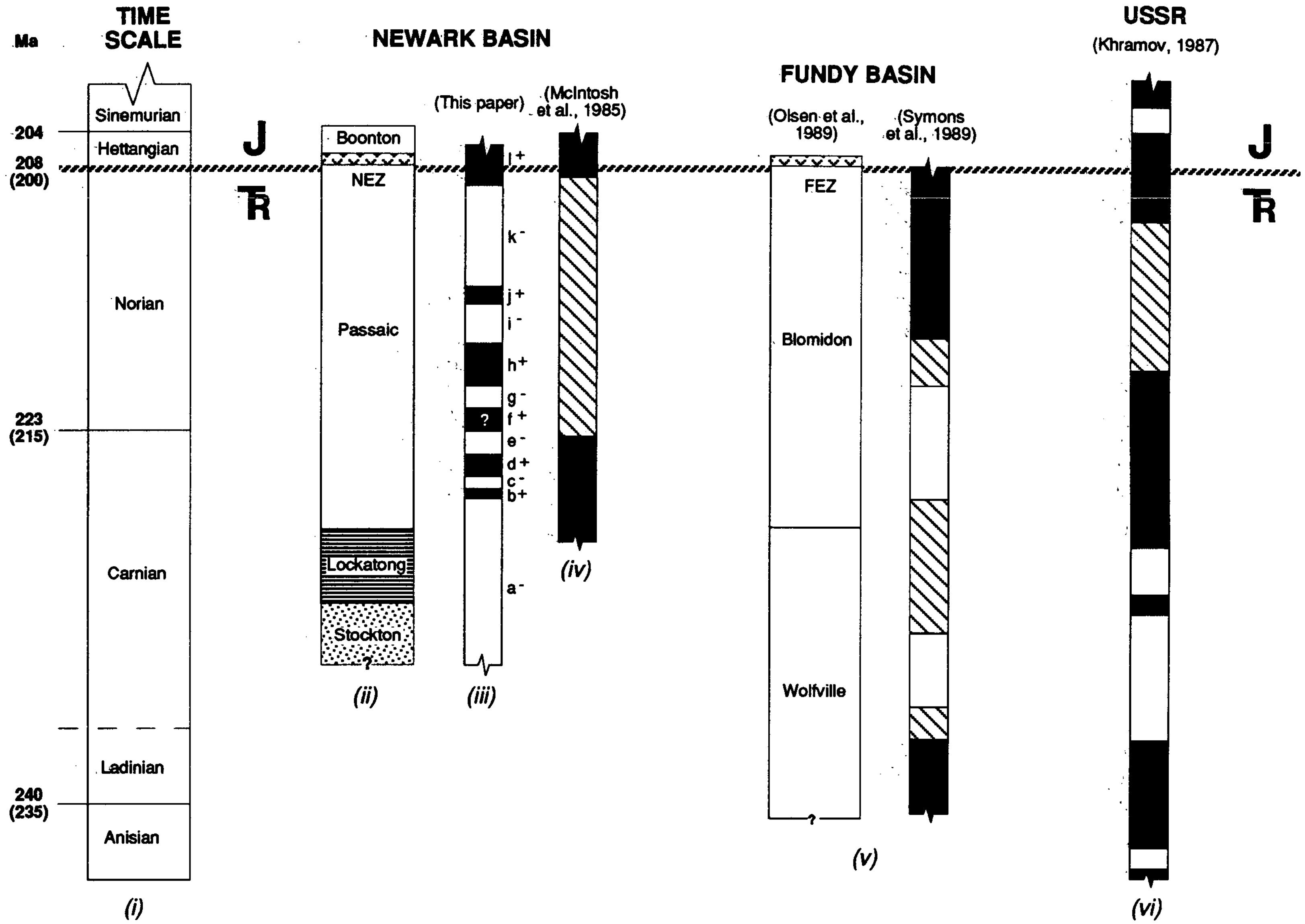


Figure 9. Comparison of available Middle Triassic to earliest Jurassic magnetic polarity sections. Column i indicates a cyclostratigraphically adjusted Middle Triassic to earliest Jurassic geologic time scale (Olsen and others, 1989) with Harland and others' (1990) numerical ages on the left (and Webb's, 1981, numerical ages in parentheses). Column ii shows the Newark basin chronostratigraphic range (Olsen and others, 1989). Column iii shows the composite polarity time scale derived in this paper. Column iv indicates the Newark results of McIntosh and others (1985). Column v displays the Symons and others (1989) polarity stratigraphy of the Fundy basin with formation ages as assigned by Olsen and others (1989). Column vi shows the Middle Triassic to earliest Jurassic portion of Khramov's (1987) Mesozoic magnetic polarity time scale adjusted to conform with column i, with the assumption that the USSR's Rhaettian and Norian are equivalent to the North American Norian. NEZ and FEZ indicate the Newark and Fundy basin extrusive zones, respectively. In columns iii to vi, black indicates normal polarity, white a reversed polarity, and diagonal lines a "mixed" polarity interpretation.

Correlation of Magnetostratigraphy to Other Sections

The initial paleomagnetic study of the entire Newark basin section by McIntosh and others (1985) provided important indications that a correlatable magnetostratigraphy could be obtained with suitable experimental procedures. We found that complete progressive thermal demagnetization on all samples was necessary to isolate consistently the characteristic component of magnetization, and this enabled us to assemble a coherent and refined magnetic polarity stratigraphy for the Newark basin sequence. Short, intrasite polarity zones were not found at any of our sites (with the obvious exception of site TGJ, which captured a reverse to normal polarity change near the base of the Ukrainian Village member). We thus suspect that the many apparent short, discontinuous magnetozones observed by McIntosh and others (1985) were due to variable amounts of unremoved overprint contamination and regard the Newark magnetostratigraphy presented in this paper (Fig. 7) as more definitive.

Elsewhere in the Newark Supergroup, paleomagnetic results from the Wolfville and Blomidon Formations suggest that a bipolar hematitic characteristic magnetization is present in the red beds of the Fundy Group, as well as formidable overprints with unblocking temperatures to perhaps 620 °C (Symons and others, 1989). Cornet and Olsen (1985) have assigned the Fundy Group of Nova Scotia an Anisian to Hettangian age and have placed the contact between the Wolfville and Blomidon Formations in the late Carnian. The oldest rocks in the Fundy basin (Anisian) are older than the oldest known Newark basin strata; thus the Fundy section could potentially add 5–10 m.y. of polarity history to the base of the Newark polarity record.

Unfortunately, stratigraphic correlation within the Fundy basin and especially the Minas sub-basin is likely to be rather complicated owing to missing and repeated portions of the section associated with numerous normal-slip and oblique-slip faults (Olsen and others, 1989; Olsen and Schlische, 1990). This, combined with the few details concerning the stratigraphic positions of sampling sites available in Symons and others (1989), limits attempts to correlate the magnetostratigraphy of the Fundy basin to the Newark basin. The "initial apparent magnetostratigraphy for the lower Fundy Group" (Symons and others, 1989) shows a long normal interval at the base of the Wolfville Formation that is probably below the Newark a^- zone and older than the oldest Newark basin rocks; the overlying reversed zone within the Wolfville Formation might correlate in part with the Newark a^- zone. The long reversed zone and the long normal zone within the Blomidon Formation, however, have no counterparts in the Newark section where the apparently correlative Passaic Formation has several normal polarity intervals followed by the Newark k^- reversed interval. Nevertheless, the Triassic/Jurassic boundary in the Fundy basin (placed in the upper Blomidon Formation; Cornet and Olsen, 1985) is apparently within an interval of normal polarity, which also includes the Fundy basin extrusive zone, similar to the Newark basin section.

Within North America, another potential source of Late Triassic geomagnetic polarity history is the Chinle Formation of the southwestern United States. Although the temporal extents of the Chinle and Newark sedimentary rocks apparently overlap (Lucas and Hunt, 1989; Olsen and Sues, 1986), the lack of agreement between the Chinle and the Newark paleomagnetic poles suggests that at least the magnetizations of the Chinle and Newark are not coeval; hence, there is no reason to believe that the sections should share the same magnetostratigraphy. In any case, the relatively small thickness and presumably low net sediment accumulation rates of the existing Chinle magnetostratigraphic sections (for example, the 145-m section thickness in Reeve and Helsley, 1972; Fig. 7) would imply relatively low temporal resolution in the Chinle, especially in comparison to the kilometers-thick Newark basin section.

Perhaps the most ambitious (and, because discussion of sampling, stratigraphic controls, and experimental procedures is scant, most difficult to evaluate) published polarity time scale that includes results from the Triassic is Khramov's (1987) Mesozoic polarity time scale. This compilation of results, primarily from the USSR, indicates a predominantly normal polarity interval in the Middle Triassic (Ladinian and Anisian), similar to that observed by Symons and others (1989) in the lower Wolfville Formation (Fig. 9). This is followed by a predominantly reversed polarity interval that is roughly correlative to the reversed polarity interval in the Wolfville Formation and perhaps the Newark a^- zone. Above this, during the middle Carnian and Norian, the polarity sequences are a poor match, although there is general agreement in the Newark, Fundy, and USSR sections, for a normal polarity interval encompassing the Triassic/Jurassic boundary, which is probably the best identified time horizon to span the three sections. It is also interesting that the USSR polarity time scale shows reversed polarity in the Sinemurian, which if correct would imply that the youngest strata thus far sampled in the Newark (Boonton Formation) do not extend into the Sinemurian.

In conclusion, the high degree of temporal continuity and the high sedimentation rates in the Newark basin strata, along with the excellent preservation of an early acquired magnetization that faithfully records the geomagnetic field direction and polarity, lead us to suggest that the Newark section has the demonstrated potential for use as a Late Triassic/earliest Jurassic magnetostratigraphic reference sequence. Further refinement of the polarity intervals is presently limited by the availability of outcrop and the uncertainties of correlation between the sections. More complete cyclostratigraphic and magnetic polarity descriptions, however, should be forthcoming from borehole studies of the section (Olsen and Kent, 1990).

ACKNOWLEDGMENTS

We are grateful for critical reviews of the manuscript by M. Van Fossen and the *Bulletin* reviewers. Additional comments and suggestions by Richard Gordon were also appreciated. This research was supported in part by the National Science Foundation, Earth Sciences Division (Grant EAR87-21142).

REFERENCES CITED

Alvarez, W., Arthur, M. A., Fischer, A. G., Lowrie, W., Napoleone, G., Premoli-Silva, I., and Roggenthen, W. M., 1977, V. Type section for the Late Cretaceous–Paleocene geomagnetic reversal time scale: Geological Society of America Bulletin, v. 88, p. 367–389.

Bazard, D. R., and Butler, R. F., 1989, Paleomagnetism of the Chinle Formation, Arizona and New Mexico: Implications for Late Triassic–Early Jurassic apparent polar wander [abs.]: Eos (American Geophysical Union Transactions), v. 70, p. 1068.

——— 1990, Late Triassic–Early Jurassic APW: A view from the southwestern United States [abs.]: Eos (American Geophysical Union Transactions), v. 71, p. 488.

Beck, M. E., 1965, Paleomagnetic and geological implications of magnetic properties of the Triassic diabase of southeastern Pennsylvania: Journal of Geophysical Research, v. 70, p. 2845–2856.

——— 1972, Paleomagnetism of Upper Triassic diabase from southeastern Pennsylvania: Further results: Journal of Geophysical Research, v. 77, p. 5673–5687.

Bowker, D. E., 1960, Remanent magnetization of eastern United States Triassic rocks [Ph.D. thesis]: Cambridge, Massachusetts, Massachusetts Institute of Technology, 155 p.

Bryan, P., and Gordon, R. G., 1990, Rotation of the Colorado Plateau: An updated analysis of paleomagnetic poles: Geophysical Research Letters, v. 17, p. 1501–1504.

Cornet, B., 1977, The palynostratigraphy and age of the Newark Supergroup [Ph.D. thesis]: State College, Pennsylvania, University of Pennsylvania, 505 p.

Cornet, B., and Olsen, P. E., 1985, A summary of the biostratigraphy of the Newark Supergroup of eastern North America with comments on early Mesozoic provinciality, *in* III Congresso Latinoamericano de Paleontologia, Mexico, Simposio Sobre Floras del Triasico Tardio, su Fitogeografia y Paleoecologia, Memoria, p. 67–81.

Dubois, P. M., Irving, E., Opdyke, N. D., Runcorn, S. K., and Banks, M. R., 1957, The geomagnetic field in the Upper Triassic times in the United States: Nature, v. 180, p. 1186–1187.

Dunning, G. R., and Hodych, J. P., 1990, U/Pb zircon and baddeleyite ages for the Palisades and Gettysburg sills of the northeastern United States: Implications for the age of the Triassic/Jurassic boundary: Geology, v. 18, p. 795–798.

Ekstrand, E. J., and Butler, R. F., 1989, Paleomagnetism of the Moenave Formation: Implications for the Mesozoic North American apparent polar wander path: Geology, v. 17, p. 245–248.

Fisher, R. A., 1953, Dispersion on a sphere: Royal Society of London Proceedings, v. A217, p. 295–305.

Gordon, R. G., Cox, A., and O'Hare, S., 1984, Paleomagnetic Euler poles and the apparent polar wander and absolute motion of North America since the Carboniferous: Tectonics, v. 3, p. 499–537.

Harland, W. B., Cox, A. V., Llellyn, P. G., Pinkton, C.A.G., Smith, A. G., and Walters, A., 1982, A geologic time scale: Cambridge, England, Cambridge University Press, 131 p.

Harland, Walter Brian, Armstrong, Richard L., Cox, Allen V., Craig, Lorraine E., Smith, Alan G., and Smith, David G., 1990, A geologic time scale, 1989: Cambridge, England, Cambridge University Press, 263 p.

Irving, E., and Banks, M. R., 1961, Paleomagnetic results from the Upper Triassic lavas of Massachusetts: Journal of Geophysical Research, v. 66, p. 1935–1939.

Irving, E., and Irving, G. A., 1982, Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana: Geophysical Surveys, v. 5, p. 141–188.

Irving, E., and Pulliah, G., 1976, Reversals of the geomagnetic field, magnetostratigraphy, and relative magnitude of paleosecular variation in the Phanerozoic: Earth Science Reviews, v. 12, p. 35–64.

Johnson, N. M., and McGee, V. E., 1983, Magnetic polarity stratigraphy: Stochastic properties of data, sampling problems, and the evaluation of interpretations: Journal of Geophysical Research, v. 88, p. 1213–1221.

Kent, D. V., and Gradstein, F. M., 1986, A Jurassic to recent chronology, *in* Vogt, P. R., and Tucholke, B. E., eds., The geology of North America, Volume M, The western North Atlantic region: Boulder, Colorado, Geological Society of America, p. 45–50.

Khramov, A. N., 1987, Paleomagnetology: Berlin, Germany, Springer-Verlag, 308 p.

Kirschvink, J. L., 1980, The least-squares line and plane and the analysis of paleomagnetic data: Royal Astronomical Society Geophysical Journal, v. 62, p. 699–718.

Klitgord, K. D., and Schouten, H., 1986, Plate kinematics of the central Atlantic, *in* Vogt, P. R., and Tucholke, B. E., eds., The geology of North America, Volume M, The western North Atlantic region: Boulder, Colorado, Geological Society of America, p. 351–378.

Kodama, K. P., 1983, Magnetic and gravity evidence for a subsurface connection between the Palisades sill and the Ladentown Basalts: Geological Society of America Bulletin, v. 94, p. 151–158.

——— 1987, Comment on "Paleomagnetism of Early Jurassic rocks, Watchung Mountains, Newark basin: Evidence for complex rotations along the border fault": Geophysical Research Letters, v. 14, p. 239–241.

Lucas, S. G., and Hunt, A. P., 1989, Revised Triassic stratigraphy in the Tucumcari basin, east-central New Mexico, *in* Lucas, S. G., and Hunt, A. P., eds., Dawn of the age of Dinosaurs in the American southwest: Albuquerque, New Mexico, New Mexico Museum of Natural History, p. 150–170.

Lyttle, P. T., and Epstein, J. B., 1987, Geologic map of the Newark 1° × 2° quadrangle, New Jersey, Pennsylvania, and New York: U.S. Geological Survey Miscellaneous Investigations Series Map I-1715.

McElhinny, M. W., 1964, Statistical significance of the fold test in palaeomagnetism: Royal Astronomical Society Geophysical Journal, v. 8, p. 338–340.

McElhinny, M. W., and Burek, P. J., 1971, Mesozoic paleomagnetic stratigraphy: Nature, v. 232, p. 98–102.

McFadden, P. L., and Jones, D. L., 1981, The fold test in paleomagnetism: Royal Astronomical Society Geophysical Journal, v. 67, p. 53–58.

McFadden, P. L., and McElhinny, M. W., 1990, Classification of the reversal test in palaeomagnetism: Geophysical Journal International, v. 103, p. 725–729.

McIntosh, W. C., Hargraves, R. B., and West, C. L., 1985, Paleomagnetism and oxide mineralogy of Upper Triassic to Lower Jurassic red beds and basalts in the Newark basin: Geological Society of America Bulletin, v. 96, p. 463–480.

Molina-Garza, R., Van der Voo, R., and Geissman, J. W., 1990, Paleomagnetic data for the Shinarump Member of the Chinle Formation in central New Mexico [abs.]: Eos (American Geophysical Union Transactions), v. 71, p. 488.

Olsen, P. E., 1986, A 40-million-year lake record of early Mesozoic orbital climatic forcing: Science, v. 234, p. 842–848.

Olsen, P. E., and Fedosh, M., 1988, Duration of the early Mesozoic extrusive igneous episode in eastern North America determined by use of Milankovitch-type cycles: Geological Society of America Abstracts with Programs, v. 20, p. 59.

Olsen, P. E., and Kent, D. V., 1990, Continental coring of the Newark rift: Eos (American Geophysical Union Transactions), v. 71, no. 15, p. 385–394.

Olsen, P. E., and Schlische, R. W., 1990, Transtensional arm of the early Mesozoic Fundy rift basin: Penecontemporaneous faulting and sedimentation: Geology, v. 18, p. 695–698.

Olsen, P. E., and Sues, H. D., 1986, Correlation of continental Late Triassic and Early Jurassic sediments and patterns of the Triassic-Jurassic tetrapod transition, *in* Padian, K., ed., The beginning of the age of dinosaurs: Faunal change across the Triassic-Jurassic boundary: Cambridge, England, Cambridge University Press, p. 321–351.

Olsen, P. E., Schlische, R. W., and Gore, P.J.W., 1989, Tectonic, depositional, and paleoecological history of the early Mesozoic rift basins, eastern North America: Washington, D.C., American Geophysical Union, Field Trip Guide Book T351, 174 p.

Opdyke, N. D., 1961, The paleomagnetism of the New Jersey Triassic: A field study of the inclination error in red sediments: Journal of Geophysical Research, v. 66, p. 1941–1949.

Palmer, A. R., 1983, The Decade of North American Geology 1983 geologic time scale: Geology, v. 11, p. 503–504.

Pechersky, D. M., and Khramov, A. N., 1973, Mesozoic paleomagnetic scale of the USSR: Nature, v. 244, p. 499–501.

Pipiringos, G. N., and O'Sullivan, R. B., 1978, Principal unconformities in Triassic and Jurassic rocks, western interior United States—A preliminary survey: U.S. Geological Survey Professional Paper 1035-A, 29 p.

Ratcliffe, N. M., 1988, Reinterpretation of the relationship of the western extension of the Palisades Sill to the lava flows at Ladentown, New York, based on new core data, *in* Froelich, A. J., and Robinson, G. R., Studies of the early Mesozoic basins of the eastern United States: U.S. Geological Survey Bulletin 1776, p. 113–135.

Reeve, S. C., 1975, Paleomagnetic studies of sedimentary rocks of Cambrian and Triassic age [Ph.D. thesis]: Dallas, Texas, University of Texas at Dallas, 426 p.

Reeve, S. C., and Helsley, C. E., 1972, Magnetic reversal sequence in the upper portion of the Chinle Formation, Montoya, New Mexico: Geological Society of America Bulletin, v. 83, p. 3795–3812.

Schlische, R. W., and Olsen, P. E., 1990, Quantitative filling model for continental extensional basins, with applications to early Mesozoic rifts of eastern North America: Journal of Geology, v. 98, p. 135–155.

Smith, T. E., and Noltimier, H. C., 1979, Paleomagnetism of the Newark trend igneous rocks of the north-central Appalachians and the opening of the central Atlantic Ocean: American Journal of Science, v. 279, p. 778–807.

Sutter, J. F., 1988, Innovative approaches to the dating of igneous events in the early Mesozoic basins of the eastern United States, *in* Froelich, A. J., and Robinson, G. R., Studies of the early Mesozoic basins of the eastern United States: U.S. Geological Survey Bulletin 1776, p. 194–200.

Symons, D.T.A., Bormann, R. E., and Jans, R. P., 1989, Paleomagnetism of the Triassic red beds of the lower Fundy Group and Mesozoic tectonism of the Nova Scotia platform, Canada: Tectonophysics, v. 164, p. 13–24.

Van Fossen, M. C., and Kent, D. V., 1990, High latitude paleomagnetic poles from Jurassic plutons and moat volcanics in New England and the controversy regarding Jurassic apparent polar wander for North America: Journal of Geophysical Research, v. 95, p. 17503–17516.

Van Fossen, M. C., Flynn, J. J., and Forsythe, R. D., 1986, Paleomagnetism of Early Jurassic rocks, Watchung Mountains, Newark basin: Evidence for complex rotations along the border fault: Geophysical Research Letters, v. 13, p. 185–188.

——— 1987, Reply to Kodama: Geophysical Research Letters, v. 14, p. 242–244.

Van Houten, F. B., 1962, Cyclic sedimentation and the origin of analcime-rich Upper Triassic Lockatong Formation, west-central New Jersey and adjacent Pennsylvania: American Journal of Science, v. 260, p. 561–576.

——— 1964, Cyclic lacustrine sedimentation, Upper Triassic Lockatong Formation, central New Jersey and adjacent Pennsylvania: Kansas Geological Survey Bulletin, v. 169, p. 497–531.

——— 1977, Triassic-Liassic deposits of Morocco and eastern North America: A comparison: American Association of Petroleum Geologists Bulletin, v. 61, p. 79–99.

Watson, G. S., and Irving, E., 1957, Statistical methods in rock magnetism: Royal Astronomical Society Monthly Notices, Geophysics Supplement, v. 7, p. 289–300.

Webb, J. A., 1981, A radiometric time scale of the Triassic: Geological Society of Australia Journal, v. 28, p. 107–121.

Witte, W. K., and Kent, D. V., 1989, A middle Carnian to early Norian (~225 Ma) paleopole from sediments of the Newark basin, Pennsylvania: Geological Society of America Bulletin, v. 101, p. 1118–1126.

——— 1990, The paleomagnetism of red beds and basalts of the Hettangian extrusive zone, Newark basin, New Jersey: Journal of Geophysical Research, v. 95, p. 17533–17545.

——— 1991, Tectonic implications of a remagnetization event in the Newark basin: Journal of Geophysical Research (in press).

Zijderveld, J.D.A., 1967, A.C. demagnetization of rocks: Analysis of results, *in* Collinson, D. W., Creer, M. K., and Runcorn, S. K., eds., Methods in paleomagnetism: New York, Elsevier, p. 254–286.

MANUSCRIPT RECEIVED BY THE SOCIETY NOVEMBER 5, 1990
REVISED MANUSCRIPT RECEIVED MAY 20, 1991
MANUSCRIPT ACCEPTED MAY 28, 1991
LAMONT-DOHERTY GEOLOGICAL OBSERVATORY CONTRIBUTION NO. 4839