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Astronomically tuned geomagnetic polarity timescale for the Late Triassic

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Abstract. Cycle stratigraphic and magnetostratigraphic analyses of a ~5000-m-thick composite section obtained by scientific coring in the Newark rift basin of eastern North America provide a high-resolution astronomically calibrated geomagnetic polarity timescale (GPTS) spanning over 30 m.y. of the Late Triassic and earliest Jurassic. Only normal polarity is found in ~1000 m of interbedded volcanics and continental sediments of earliest Jurassic age but a total of 59 normal and reverse polarity magnetozones are delineated in the underlying 4000+ m of Late Triassic continental sediments. Lithologic facies response to climatically induced lake level variation provides a full spectrum of Milankovitch cyclicity; the prominent 404 kyr orbital eccentricity climate cycle has a mean thickness of about 60 m and is the basis for scaling most of the stratigraphic section in time. When indexed to available radioisotopic dating, the resulting astronomically calibrated GPTS spans from the 202 Ma Triassic/Jurassic boundary to 233 Ma. Results of detailed sampling profiles across 42 magnetozone boundaries representing 35 different polarity reversals indicate transition durations that average 7.9 kyr, comparable to the estimated duration of recent polarity reversals. The polarity intervals have a mean duration of 0.53 m.y. with a corresponding reversal rate of 1.88 m.y.$^{-1}$ and no significant polarity bias and are closely approximated by an exponential distribution with a gamma index k indistinguishable from 1. The longest polarity interval is about 2 m.y., and the shortest is about 0.02 m.y. The overall statistical properties indicate that the behavior of the geomagnetic field in the Late Triassic was not very different from that in the Cenozoic. This geomagnetic polarity record of the Late Triassic provides a well-dated chronostratigraphic framework suitable for detailed global correlation.

1. Introduction

The efficacy of magnetostratigraphic correlations relies on the identification of a characteristic temporal sequence of normal and reverse polarity intervals. A geomagnetic polarity timescale (GPTS) also provides one of the few lines of empirical evidence for the evolution of the geodynamo [*McFadden and Merrill*, 1984; *Courtillot and Besse*, 1987; *Larson and Olson*, 1991]. However, geomagnetic polarity history is well known over only about the past 175 m.y. where the availability of numerous marine magnetic anomaly profiles from extant modern ocean floor allows the construction of a complete reference sequence of polarity reversals [e.g., *Cande and Kent*, 1992, 1995; *Channell et al., 1995*]. This detailed polarity record, calibrated by magnetobiostratigraphic correlations of several well-dated tiepoints, constitutes a framework for virtually all modern integrated geologic timescales for the late Jurassic, Cretaceous and Cenozoic [*Gradstein et al.*, 1995; *Berggren et al.*, 1995a].

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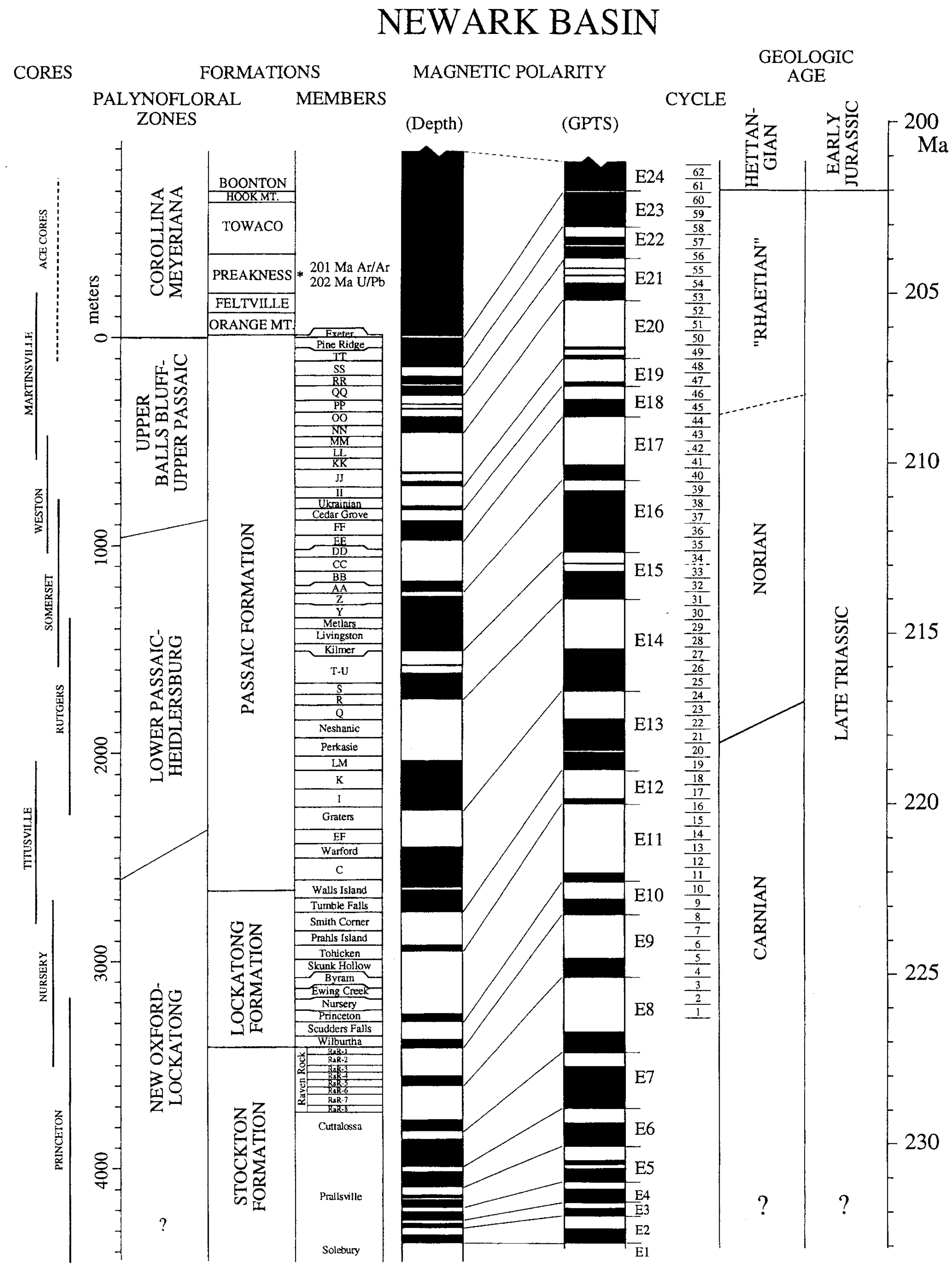
The development of a geomagnetic polarity timescale (GPTS) for earlier time intervals has been much slower and has relied on piecing together magnetostratigraphic records of variable length, fidelity, and chronological control (see review by *Opdyke and Channell* [1996]). Progress would clearly be expedited by long reference sections, i.e., stratigraphic analogues to magnetic anomaly profiles. In this regard, a thick and complete continental section was recently cored by scientific and geotechnical drilling in the Newark rift basin of eastern North America. Cycle stratigraphic and magnetostratigraphic analyses of this ~5000-m-thick composite section provide the basis for a candidate GPTS for virtually all of the Late Triassic and the lowermost Jurassic [*Kent et al.*, 1995; *Olsen and Kent*, 1996; *Olsen et al.*, 1996 a,b].

In this paper, we present a refinement of the initial magnetostratigraphic results for the Newark basin section by determining the thickness and duration of polarity transition zones and confirming short polarity intervals with additional sampling. The cycle stratigraphy has also been extended to older strata by the definition of eight new members. We are thus able to calculate an astronomically tuned GPTS for over 24 m.y. of the late Triassic using a methodology similar in concept to that employed with great success but independent of the seafloor record in the late Neogene [*Shackleton et al.*, 1990; *Hilgen*, 1991; *Berggren et al.*, 1995b]. Almost a further 7 m.y. of record is obtained by extrapolation of


NEWARK BASIN
CORES
FORMATIONS
MAGNETIC POLARITY
GEOLOGIC AGE
PALYNOFLORAL ZONES
MEMBERS
CYCLE
(Depth)
(GPTS)
ACE CORES
MARTINSVILLE
WESTON
SOMERSET
RUTGERS
TITUSVILLE
NURSERY
PRINCETON
meters
0
1000
2000
3000
4000
COROLLINA MEYERIANA
UPPER PASSAIC UPPER BALLS BLUFF-
LOWER PASSAIC-HEIDLERSBURG
NEW OXFORD-LOCKATONG
?
BOONTON
HOOK MT.
TOWACO
PREAKNESS
FELTVILLE
ORANGE MT.
201 Ma Ar/Ar
202 Ma U/Pb
PASSAIC FORMATION
LOCKATONG FORMATION
STOCKTON FORMATION
Exeter
Pine Ridge
TT
SS
RR
QQ
PP
OO
NN
MM
LL
KK
JJ
II
Ukrainian
Cedar Grove
FF
EE
DD
CC
BB
AA
Z
Y
Metlars
Livingston
Kilmer
T-U
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Neshanic
Perkasie
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Graters
EF
Warford
C
Walls Island
Tumble Falls
Smith Corner
Prahls Island
Tohicken
Skunk Hollow
Byram
Ewing Creek
Nursery
Princeton
Scudders Falls
Wilburtha
Raven Rock
RaR-1
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2
1
HETTAN-GIAN
"RHAETIAN"
NORIAN
CARNIAN
?
EARLY JURASSIC
LATE TRIASSIC
?
200 Ma
205
210
215
220
225
230

sedimentation rates determined by cycle stratigraphy. Although not contiguous in age with the seafloor record, the 31-m.y.-long GPTS based on the Newark succession is sufficiently long and precise for comparative statistical analysis of the reversal sequence.

2. Background

The potential for detailed linkage of cycle stratigraphy and magnetostratigraphy in the Newark basin sequence was indicated in studies of the discontinuous outcrop [e.g., *Witte et al.*, 1991] and motivated scientific drilling under the Newark Basin Coring Project (NBCP) [*Olsen and Kent*, 1990]. Continuous coring with virtually complete recovery at seven drill sites produced a total of 6770 m of core representing practically the entire section of Upper Triassic continental sediments as well as some of the lowermost Jurassic interbedded continental sediments and lavas of the Newark igneous extrusive zone. Accounting for ~30% redundancy between the stratigraphically overlapping cored sections and normalizing the relative thicknesses to a representative core site (Rutgers), a 4660-m-thick composite section was assembled [*Olsen et al.*, 1996a]. The remainder of the Jurassic section was studied in a series of geotechnical test borings by the Army Corps of Engineers [*Fedosh and Smoot*, 1988; *Witte and Kent*, 1990; *Witte et al., 1991*; *Olsen et al.*, 1996b]. The lithostratigraphy, magnetostratigraphy, and cycle stratigraphies of the composite section of >5000-m aggregate thickness are summarized in Figure 1.

The Stockton Formation is the lowermost stratigraphic unit and consists of buff-colored to red arkosic siltstones and sandstones of predominantly fluvial to shallow lacustrine facies. There are hardly any age diagnostic fossils in the lower and middle Stockton Formation, but palynostratigraphy indicates a Carnian age for at least the upper Stockton Formation [*Cornet*, 1977, 1993; *Cornet and Olsen*, 1985]. The overlying Lockatong (Carnian) and Passaic (latest Carnian to earliest Hettangian) formations consist of lacustrine deposits that display a pronounced cyclic variation in lithofacies related to depth of water. These cyclic changes in lake level are climatically induced and occur in a hierarchical pattern consistent with Milankovitch orbital forcing [*Van Houten*, 1964; *Olsen*, 1986; *Olsen and Kent*, 1996].

The fundamental Milankovitch variation is the Van Houten cycle which is recognized on a stratigraphic scale of 3 m to 6 m in the NBCP cores and corresponds to climate change at precessional periodicities (~20 kyr). The expression of Van Houten cycles is modulated by several orders of orbital eccentricity variations, especially with periods around 100 kyr and most prominently by the 404-kyr eccentricity orbital variation which we have referred to as the McLaughlin cycle [*Olsen*, 1986; *Olsen and Kent*, 1996].

The McLaughlin cyclicity effectively corresponds to the mappable lithostratigraphic members of the Lockatong and Passaic Formations. Although the absolute lithologic expression of the cycles varies considerably as a result of the evolution of the basin and lateral position within the basin, as well as the possible effects of even longer orbital cycles [*Olsen and Kent*, 1999], the 404-kyr McLaughlin cycle is a robust variation that can be traced throughout the lacustrine facies of the Lockatong and Passaic Formations. A subtle expression of the McLaughlin cycle also provides the basis for a cycle stratigraphy in the very shallow lacustrine to fluvial sediments of the upper Stockton Formation where we can identify eight new members, from top to bottom, RaR-1 to RaR-8, where RaR stands for the Raven Rock locality where this part of the Stockton Formation is known to be well exposed. The 404-kyr eccentricity cycle [*Laskar*, 1990; *Berger and Loutre*, 1991] appears to be the most stable orbital periodicity over geologic time [*Berger et al.*, 1992; *Laskar et al.*, 1993]. Accordingly, the 404-kyr McLaughlin cycle is used as the basis of a homogeneous age model for the Newark section.

We recognize 60 full McLaughlin cycles or lithostratigraphic members in the NBCP cores, 52 as identified in the Lockatong and Passaic Formations by *Olsen et al.* [1996a] plus the eight new cycles in the uppermost Stockton Formation (Figure 1). A histogram of McLaughlin cycle thicknesses shows a single, well-defined peak at about 60 m (Figure 2a). An additional cycle corresponding to the Exeter member in the uppermost Passaic Formation contains the Triassic/Jurassic boundary but is interrupted by the Early

Figure 1. (opposite) Composite section of continental sediments and some interbedded basalt in the Newark basin based on seven long NBCP drill cores [*Olsen et al.*, 1996a] and a series of Army Corps of Engineers (ACE [*Fedosh and Smoot*, 1988] whose stratigraphic ranges are shown at left. Depth in composite section is based on stratigraphic thicknesses normalized to Rutgers drill core using lithologic and log correlations in overlap intervals [*Olsen et al.*, 1996a]. Palynofloral zonation [*Cornet*, 1977, 1993; *Cornet and Olsen*, 1985] was based on outcrop samples and provides the stage-level biostratigraphic dating. The $^{40}Ar/^{39}Ar$ dates of 201±1.7 Ma [*Sutter*, 1988] and U-Pb zircon dates averaging 202±1 Ma [*Dunning and Hodych, 1990*] are for Palisade sill which is most likely equivalent to the Preakness Basalt. Formations and members are described by *Olsen et al.* [1996a, b] with 8 new members (RaR-1 to RaR-8) in upper part of Stockton Formation. Magnetostratigraphy (normal polarity in filled and reverse polarity in open bars) of NBCP cores from *Kent et al.* [1995] and this paper. Magnetostratigraphy of Jurassic igneous extrusive zone (Orange Mountain Basalt, Feltville Formation, Preakness Basalt, Towaco Formation, Hood Mt. Basalt) and Boonton Formation includes data from *McIntosh et al.* [1985], *Prevot and McWilliams* [1989], *Witte and Kent* [1990], and *Witte et al.* [1991]. Magnetozone depths (using refined boundaries determined in this paper for magnetozones in Passaic Formation) were converted to a GPTS by assuming each lithologic member is a 404-kyr McLaughlin cycle and indexing the interpolated relative chronology to an estimated age of 202 Ma for the Triassic/Jurassic boundary. Polarity chrons are labeled E1 to E24 from *Kent et al.* [1995]. Note that Chron E24 is renamed from E23n.2n in the original Newark nomenclature of *Kent et al.* [1995] and corresponds to the long normal polarity magnetozone that begins just below the Triassic/Jurassic boundary and extends through the Jurassic extrusive zone into the Boonton Formation.

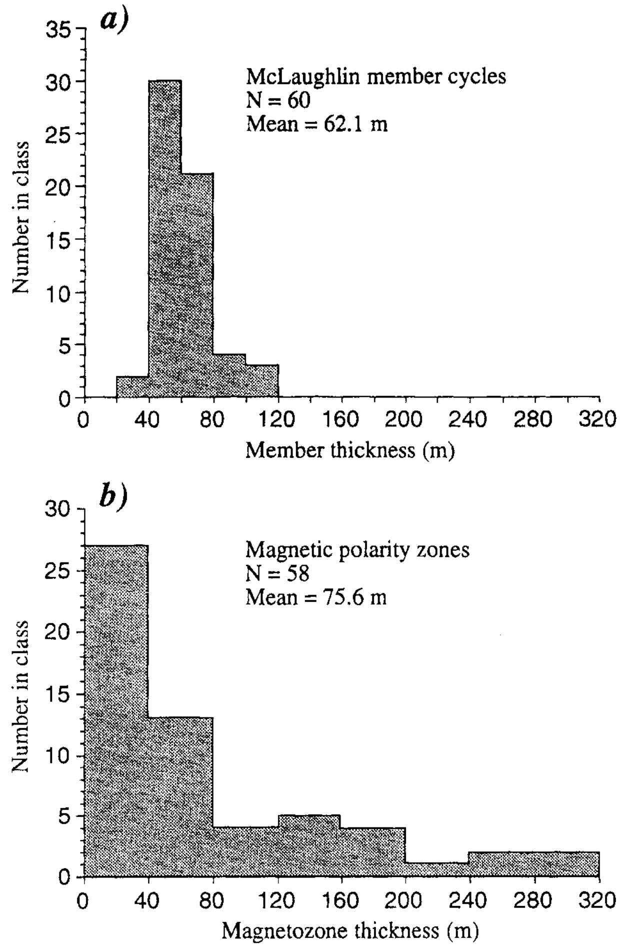

Figure 2. Histogram of thicknesses of (a) McLaughlin lithologic member cycles, and (b) magnetic polarity zones in upper Triassic sediments recovered in NBCP drill cores from Newark Basin section.

Jurassic Orange Mountain Basalt. However, cycle stratigraphic analysis of the sedimentary units interbedded with the three major basalt flow units in the Newark basin indicates that the igneous activity occurred over only one or two albeit very thick McLaughlin cycles, or a total duration of about 580 kyr, in the earliest Jurassic [*Olsen et al.*, 1996b].

A total of 60 normal and reverse magnetic polarity intervals (Chrons E1r to E24n) were delineated in the composite profile for the Stockton, Lockatong and Passaic Formations [*Kent et al.*, 1995] (Figure 1). The very thick normal polarity magnetozone (E24n) which encompasses the lower Jurassic igneous extrusive zone and Boonton Formation has been elevated in rank from its previous designation (E23n.2n) on the strength of data supporting the existence of the preceding short reverse polarity interval (E23n.1r, which has in turn become E23r). The top of this uppermost magnetozone E24n as well as the base of the lowermost reverse polarity interval (E1r) in the Stockton Formation were not recovered. Excluding these from consideration leaves 58 complete magnetozones of which 42 (E9n to E23r, formerly designated as E23n.1r) are fully represented in the cyclical part of the section.

The NBCP cores were originally sampled at 2.5-m to 3-m intervals. The magnetostratigraphy was based on vector endpoint analyses of complete progressive thermal demagnetization; characteristic magnetizations were isolated over the highest unblocking temperature range, whereas magnetic overprints recovered over low to moderate unblocking temperatures were used to azimuthally orient the samples [*Kent et al.*, 1995]. Data recovery rates were lowest (only ~60%) in the Lockatong and Stockton Formations because of less favorable magnetic properties in the dark shales and coarse buff-colored sandstones in these units whereas the predominantly red siltstones of the Passaic Formation (represented in five of the seven drill cores) yielded useful magnetic data in >85% of the samples. The average net magnetostratigraphic resolution was ~3.3 m, which in the cyclical Lockatong and Passaic formations corresponds to the nominal thickness of the 20-kyr Van Houten cycle [*Olsen and Kent*, 1996]. Although the overall number of magnetic polarity intervals is similar to the number of McLaughlin cycles, a histogram of polarity interval thickness resembles an exponential distribution (Figure 2b) compared with the more bell-shaped or Gaussian distribution of cycle thickness (Figure 2a).

3. Duration of Polarity Transitions

To refine the stratigraphic position of the polarity magnetozones and to obtain constraints on the duration of the polarity transitions, we resampled magnetozone boundaries in the Passaic Formation at a closer spacing of nominally 0.3 m. About 3 to 6 m of section that bracketed the change in polarity identified previously [*Kent et al.*, 1995] were sampled in 42 profiles representing the 35 polarity transitions (seven redundantly) bounding magnetozones E13n to E23r as recorded in the Martinsville, Weston, Somerset, Rutgers, and Titusville drill cores. Polarity transitions for magnetozones E1r to E12r recorded in the Nursery and Princeton drill cores were not resampled because of anticipated low data recovery rates in the dark shale facies in the Lockatong Formation and the more heterogeneous fluvial to shallow lacustrine facies in the upper Stockton Formation, as well as the absence of cycle stratigraphic age control in the lower and middle Stockton Formation. The new samples were processed according to the same laboratory techniques, analytical methods, and data acceptance criteria described by *Kent et al.* [1995]. Examples of transition records are shown in Figure 3.

Apparent changes in polarity occur over stratigraphic intervals that range from <0.5 m to >4 m, and average 1.50±0.83 m (standard deviation) for the 42 records (Figure 4a). It is possible that some of the very thin polarity transitions may represent local hiatuses. Other transitions may appear expanded due to either prolonged magnetization acquisition [e.g., *Channell et al.*, 1982] or the inclusion of intermediate magnetization directions (i.e., VGP latitudes more than 30° from polar) that may be artifacts of poor recording properties or superposed magnetization vectors [e.g., *Langereis et al.*, 1992; *Kent and Schneider*, 1995]. However, intermediate directions as well as more poorly resolved magnetization components that tend to occur in samples from magnetozone boundaries may also reflect acquisition in weak, transitional geomagnetic fields during polarity reversals. In any case, the close congruity of magnetozone boundaries with respect to lake level cycles over

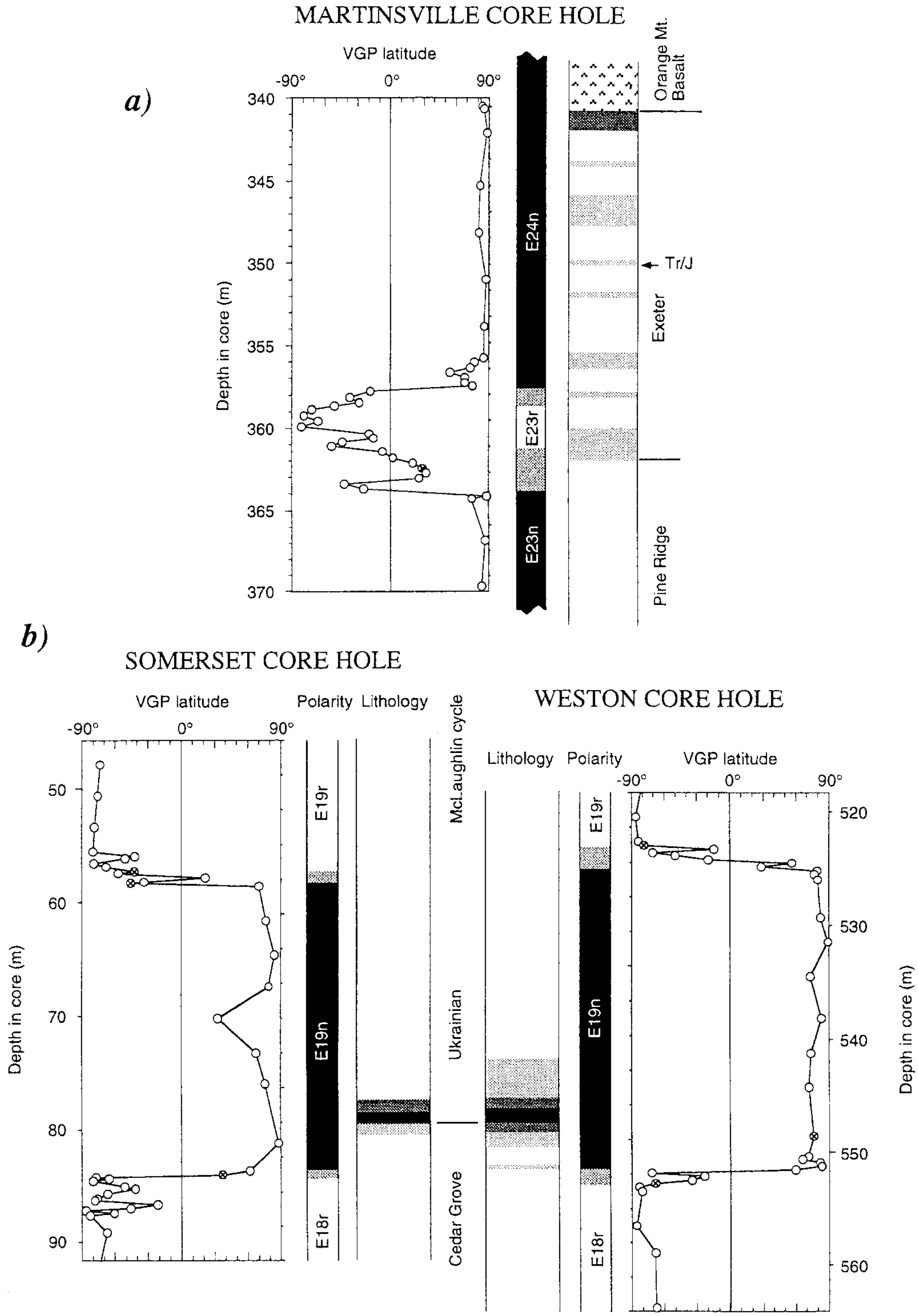

Figure 3. Polarity transition records for (a) magnetozone E23r (formerly E23n.1r) in the Martinsville drill core, just below the contact with the Orange Mountain Basalt, and (b) magnetozone E19n in the upper part of the Somerset drill core and the lower part of the Weston drill core which were correlated on the basis of the Ukrainian member which has a prominent black shale at its base. Virtual geomagnetic pole (VGP) latitudes are for characteristic magnetizations determined from principal component analysis of generally the 650° to 680°C thermal demagnetization steps and oriented azimuthally using overprint magnetizations (see *Kent et al.* [1995] for details). Circles with crosses are samples with poorly defined characteristic magnetization (MAD>15°). Polarity column is solid for normal polarity, open for reverse polarity, and stippled for uncertain or intermediate (VGP latitudes ±60°) directions. For reference, Chron E19n has a duration of 0.151 m.y. according to cycle stratigraphy, whereas Chron E23r has a estimated duration of 0.026 m.y. and is one of the shortest polarity intervals in the Newark GPTS. Lithology column shows gradations from red siltstones (open) to gray (stippled) and black (solid) shales, and the Orange Mountain Basalt in the Martinsville drill core.

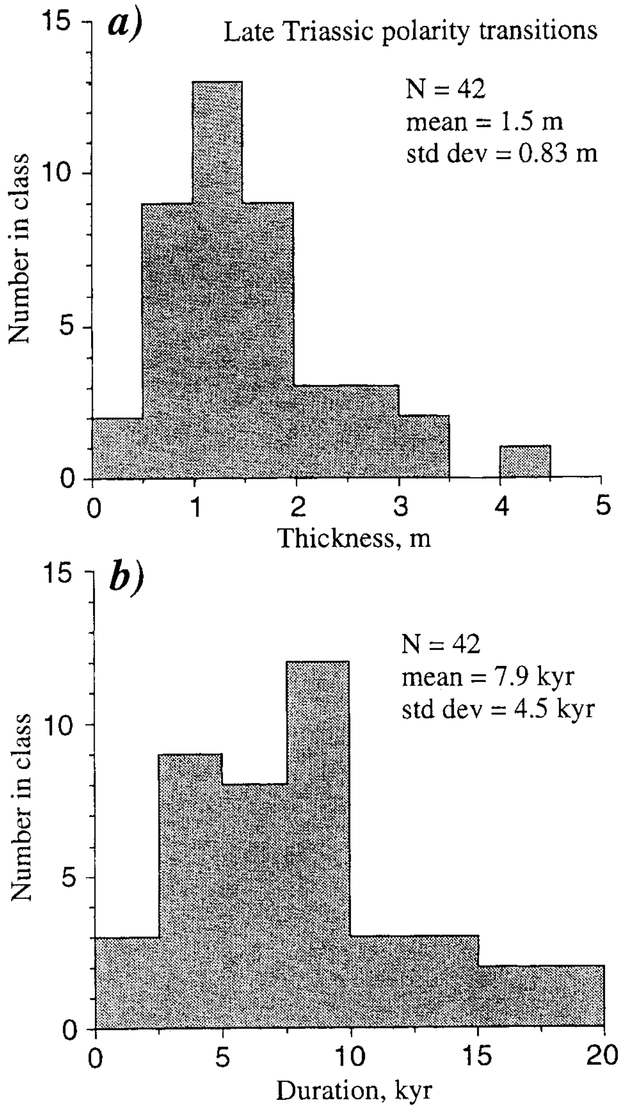

Figure 4. Histograms of (a) thicknesses and (b) the corresponding durations for 42 magnetozone polarity transitions representing 35 geomagnetic reversals sampled in the Passaic Formation in NBCP cores. Sampling interval was nominally 0.3 m. Durations estimated using local sedimentation rates from enclosing or nearest 404-kyr. McLaughlin member cycle.

lateral distances of tens of kilometers in the Newark Basin (e.g., Figure 3 and *Kent et al.* [1995] and *Olsen et al.* [1996a]) suggests that the magnetizations were acquired close to the time of deposition. We therefore suggest that intermediate or poorly defined directions at magnetozone boundaries can be used to approximate the polarity transition interval in these Late Triassic sediments.

The transition zone thicknesses were converted to time based on sediment accumulation rates calculated for the enclosing 404-kyr McLaughlin member cycle in terms of its actual (not normalized) stratigraphic thickness; these local sediment accumulation rates vary from ~100 to 300 m m.y.$^{-1}$ and average 191 m m.y.$^{-1}$ For four transition records that occur in a McLaughlin member cycle whose base or top was not recovered at the bottom or top of a drill core, the sediment accumulation rate for the immediately adjacent complete McLaughlin member-cycle was used. The 42 records give transition durations ranging from 1.8 to 20 kyr with a mean of 7.9±4.5 kyr (Figure 4b). This compares favorably with estimates of about 4 to 10 kyr for the duration of the Brunhes/Matuyama, the most recent and best documented geomagnetic reversal transition [e.g., *Clement and Kent*, 1984]. From the standpoint of correlation, the estimated mean duration of polarity transitions in the Newark section indicates that the practical limit of magnetostratigraphic resolution should be better than about one-half of a 20-kyr Van Houten orbital precession cycle.

4. Geomagnetic Polarity Timescale

To construct a geomagnetic polarity timescale, we use an age model that assumes that each of the 60 complete lithostratigraphic members in the cyclical uppermost Stockton, Lockatong and Passaic Formations represents a 404-kyr orbital eccentricity cycle. The cyclical late Triassic portion of the Newark basin section thus represents over 24 m.y. of sediment accumulation with an average rate of 160 m m.y.$^{-1}$ based on normalized thicknesses (Figure 5).

The relative ages of magnetozone boundaries (midpoints of the polarity transitions) were determined by linear interpolation within the enclosing or nearest 404-kyr McLaughlin member cycles. Where the same magnetozone was identified in stratigraphically overlapping drill cores, the average interpolated position within the correlative McLaughlin member-cycle was used (rather than just the downdip portion of each overlap record as done by *Kent et al.* [1995]). Between-core differences as a decimal fraction of a McLaughlin cycle average 0.018, equivalent to about 7.5 kyr, which is of the order of the calculated mean transition duration and effective magnetostratigraphic resolution.

The ages for magnetozones E9r and E9n can now be determined by interpolation using the eight newly recognized McLaughlin member cycles (RaR-1 to RaR-8) at the top of the Stockton Formation in the Princeton drill hole. Moreover, the average sediment accumulation rate of 96.2 m m.y.$^{-1}$ calculated for these cycles in normalized depth units is used to extrapolate ages for magnetozones E1r to E8r in the noncyclical lower and middle part of the Stockton Formation in the Princeton drill core. Previously, a sediment accumulation rate of 140 m m.y.$^{-1}$ based on the cycles in the lower Lockatong Formation was used to extrapolate the ages of all Stockton magnetozones (E1r to E9r) in the Princeton drill core [*Kent et al.*, 1995].

The internal cycle chronology is indexed to an absolute geologic time framework by concordant dates of 201±2.7 Ma ($^{39}Ar/^{40}Ar$ [*Sutter*, 1988]) and 202±1 Ma (U/Pb zircon [*Dunning and Hodych*, 1990]), or a simple average of 201.5 Ma for the Palisade sill. Physical and geochemical evidence suggests that the Palisade sill is most likely contemporaneous with the second (Preakness Basalt) of the three major lava units in the Watchung syncline [*Kodama*, 1983; *Ratcliffe*, 1988]. The exact correlation between the Palisade sill and the basaltic extrusive rocks, however, is not very critical because the difference in age between the oldest and youngest lavas is only 580 kyr according to cycle stratigraphy of the interbedded sediments [*Olsen et al.*, 1996b]. This age span is well within the quoted analytical uncertainty of the isotopic

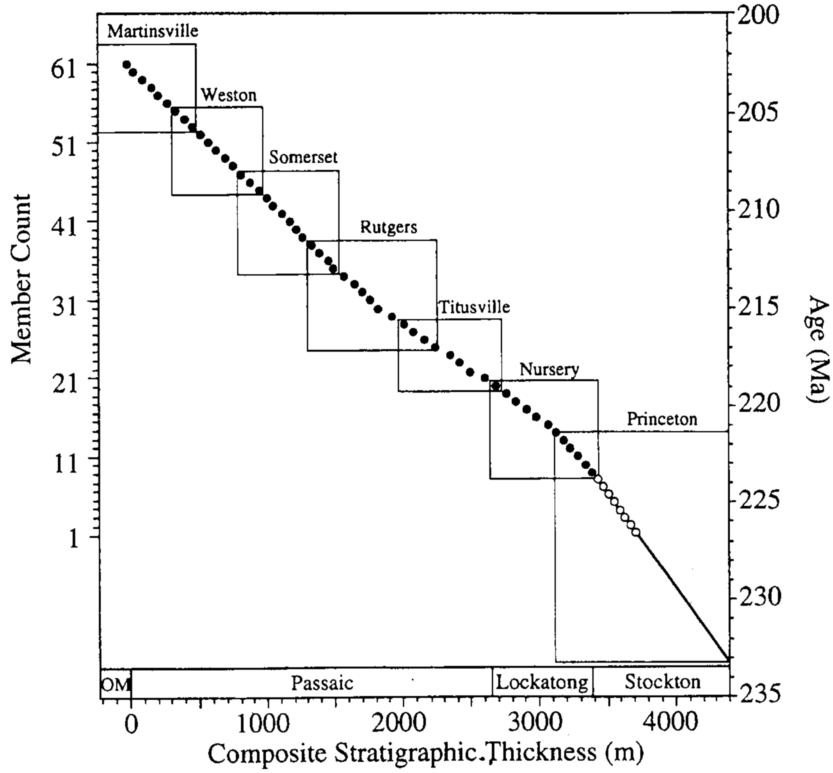

Figure 5. Ordinal series of lithologic members (McLaughlin cycles) with respect to composite depth (normalized to the Rutgers drill core) in NBCP cores (solid circles [*Kent et al.*, 1995]) with addition of eight new members in upper Stockton Formation (open circles). Age model assumes each McLaughlin cycle represents 404 kyr and a date of 202 Ma for the Triassic/Jurassic boundary in lower part of Exeter Member (61st cycle). Boxes are stratigraphic intervals and corresponding age ranges represented in the NBCP drill cores. Diagonal line in box for Princeton drill core shows extrapolated sedimentation rates from the eight new members in upper Stockton Formation.

dates. The palynological Triassic/Jurassic boundary lies in the uppermost Passaic Formation, within the second Van Houten cycle above the base of the Exeter Member and one or two Van Houten cycle (~30 kyr) below the local equivalent of the Orange Mountain Basalt [*Fowell and Olsen*, 1993]. The Preakness Basalt is separated from the Passaic Formation by the Feltville Formation and the Orange Mountain Basalt. Assuming that the Exeter Member is the initial part of the McLaughlin cycle that also includes the Feltville Formation (as well as the negligible geologic time span thought to be represented by the intervening Orange Mountain Basalt), we obtain a rounded estimate of 202 Ma for the age of the Triassic/Jurassic boundary.

The North Mountain Basalt of the Fundy Basin has produced U-Pb zircon dates averaging 202±1 Ma which support a comparable age for the nearly suprajacent Triassic/Jurassic boundary in that basin [*Hodych and Dunning*, 1992]. An age of 202 Ma for the Triassic/Jurassic boundary is not significantly different than the age of 205.7±4.0 Ma quoted for this system boundary in the most recent Mesozoic timescale of *Gradstein et al.* [1995]. Moreover, preliminary U-Pb dates on ash layers in ammonoid-bearing marine strata from the North American Cordillera also suggest a younger age of ~200 Ma for the Triassic/Jurassic boundary [*Palfy et al.*, 1998]. Triassic chronology in light of Newark cycle stratigraphy is discussed further by *Kent and Olsen* [1999].

We use an age of 202 Ma for the Triassic/Jurassic boundary as recorded in the Newark Basin to anchor the relative timing of the McLaughlin cycles. The magnetic polarity chrons interpolated from this cycle stratigraphy are used to construct a GPTS for >30 m.y. of the Late Triassic (Table 1).

5. Statistical Analysis of Reversal Sequence

For the Late Triassic GPTS from the Newark Basin, a total of 59 polarity reversals defines 58 complete polarity intervals (E2n to E23r (formerly E23n.1r)) spanning 30.80 m.y. The mean duration of the polarity intervals is 0.53 m.y., corresponding to a mean reversal rate of 1.88 m.y.$^{-1}$. The 29 normal and the 29 reverse polarity intervals have similar mean durations (0.50 and 0.56 m.y., respectively), and with normal polarity occupying 47% and reverse polarity 53% of the total time span, there is no significant polarity bias. Similar statistical measures are obtained for the 42 polarity intervals (E9n to E23r) encompassing 23.00 m.y. with direct astronomical age control: mean interval duration is 0.55 m.y., mean reversal rate is 1.83 m.y.$^{-1}$, and the normal and reverse polarity intervals have mean durations of 0.49 and 0.61 m.y., respectively.

There are long-term fluctuations in reversal rate in the range of ~1.5 to 3 m.y.$^{-1}$. Higher reversal rates tend to occur at both the beginning and end of the sequence, but there is no

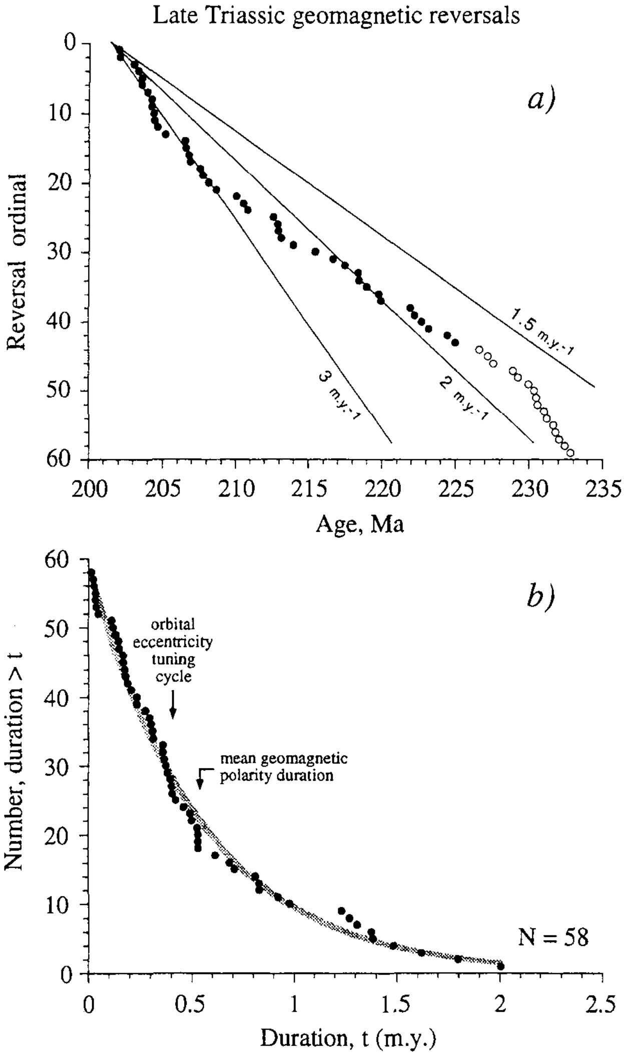

Figure 6. (a) Ordinal sequence of 59 geomagnetic reversals for Newark GPTS (Chrons E2n to base of E23r inclusive) versus age as determined in NBCP drill cores. Solid circles are 43 reversal ages interpolated from enclosing McLaughlin cycle; open circles are 16 reversal ages based on extrapolation of sedimentation rates from cycle stratigraphy to lower part of Stockton Formation in Princeton drill core. Lines of constant reversal rate are shown for reference; mean reversal rate for entire Newark GPTS is 1.88 m.y.$^{-1}$. (b) Cumulative distribution of 58 polarity intervals in Newark GPTS. Curved line is a best fit exponential curve through the data shown for reference. Mean duration of polarity intervals (0.53 m.y.) and the 404-kyr orbital eccentricity cycle used for age calibration are shown by arrows.

discernable overall trend (Figure 6a). The polarity interval lengths are approximated by an exponential distribution (Figure 6b). Assuming that the reversal sequence cannot be excluded as being stationary, we calculate a gamma index k for the distribution according to the maximum likelihood method described by *McFadden* [1984]. The estimated value of k is 1.09 for the entire sequence of 58 polarity intervals and 0.93 for the subset of 42 reversals with direct cycle stratigraphic age control. Given that the variances in the estimates of ln [k] are of order 0.05 (standard deviation of ln [k]= 0.22), it would be difficult to reject the null hypothesis that the polarity interval lengths have an exponential distribution (k = 1).

6. Discussion and Conclusions

The Late Triassic GPTS based on the Newark magnetocyclostratigraphic record reveals an almost idealized geomagnetic field reversal behavior. There is no polarity bias, and the average polarity transition duration of about 8 kyr is similar to duration estimates for recent polarity transitions. Moreover, the exponential distribution of polarity interval lengths is a characteristic feature of an underlying Poisson stochastic process as suggested by *Cox* [1968, 1969] and advocated by *McFadden* [1984] for the heretofore much better known Cenozoic record of geomagnetic reversals. These attributes support our contention that the Newark polarity sequence represents a high fidelity record of Late Triassic geomagnetic reversals.

Assuming that the McLaughlin cycles represent the 404-kyr orbital eccentricity variation, which is perhaps the most

Table 1. Newark Geomagnetic Polarity Timescale

Chron	Cycle	Depth, m	Age, Ma
Tr/J	~61.55	5.20	202
E24n	~61.036	10.70	202.021
E23r	60.970	13.81	202.048
E23n	58.550	152.40	203.026
E22r	57.796	197.66	203.330
E22n.2n	57.215	230.95	203.565
E22n.1r	57.188	232.56	203.576
E22n.1n	56.284	288.37	203.941
E21r.3r	55.506	333.30	204.256
E21r.2n	55.452	336.13	204.277
E21r.2r	55.123	353.60	204.410
E21r.1n	55.004	359.91	204.458
E21r.1r	54.536	392.43	204.647
E21n	53.225	476.59	205.177
E20r.2r	49.817	665.17	206.554
E20r.1n	49.728	671.93	206.590
E20r.1r	49.295	705.49	206.765
E20n	49.001	728.29	206.884
E19r	47.309	822.47	207.567
E19n	46.938	843.44	207.717
E18r	45.994	898.64	208.098
E18n	44.694	989.62	208.624
E17r	41.272	1183.36	210.006
E17n	40.133	1237.91	210.466
E16r	39.400	1269.25	210.762
E16n	34.953	1522.63	212.559
E15r.2r	34.180	1584.29	212.871
E15r.1n	34.101	1590.54	212.903
E15r.1r	33.589	1631.20	213.110
E15n	31.529	1756.62	213.942
E14r	27.855	2044.20	215.427
E14n	24.813	2289.78	216.656
E13r	22.800	2459.37	217.469
E13n.2n	20.521	2664.26	218.390
E13n.1r	20.434	2671.36	218.425
E13n.1n	19.125	2771.97	218.953
E12r	17.070	2933.36	219.784
E12n	16.650	2962.84	219.953
E11r	11.692	3266.94	221.956
E11n	11.011	3305.07	222.232
E10r	9.781	3382.40	222.728
E10n	8.567	3430.38	223.219

Table 1. (continued)

Chron	Cycle	Depth, m	Age, Ma
E9r	5.429	3559.70	224.487
E9n	4.118	3613.94	225.016
E8r		3773.60	226.634
E8n		3832.42	227.245
E7r		3868.33	227.619
E7n		3993.95	228.924
E6r		4028.58	229.284
E6n		4096.51	229.990
E5r		4134.42	230.384
E5n.2n		4148.57	230.531
E5n.1r		4159.59	230.645
E5n.1n		4198.22	231.047
E4r		4215.44	231.226
E4n		4256.14	231.649
E3r		4272.33	231.817
E3n		4295.08	232.054
E2r		4329.60	232.412
E2n		4368.65	232.818
E1r (partim)		(4400.85)	(233.153)

Chron is magnetic polarity interval defined in NBCP cores whose polarity is designated by suffix n for normal and r for reversed (see *Kent et al.* [1995] for further explanation of nomenclature). The base of each chron is given as the fractional position from the base of the enclosing McLaughlin member cycle, counted upsection from RaR-8 (informal cycle 1) in Stockton Formation to Exeter Member (informal cycle 61) in uppermost Passaic Formation. The Exeter Member is truncated by Orange Mountain Basalt, hence position of Triassic/Jurassic (Tr/J) boundary and the base of Chron E24n within the Exeter Member are according to Van Houten cycles from correlative outcrop exposures [*Fowell and Olsen*, 1993]; note also that Member T-U is considered as concatenation of two member cycles (see Figure 1). Depth is composite stratigraphic thickness scaled downward from base of Orange Mountain Basalt and normalized to Rutgers drill core based on successive core overlap correlations [*Olsen et al.*, 1996a]. Ages for the base of Chrons E9n to E24n are based on interpolation within McLaughlin member cycles which are assumed to represent the 404-kyr orbital eccentricity variation. Ages for the base of Chron E1r (partim), which is also the base of the NBCP section, to Chron E8r are based on extrapolation of sedimentation rates in Princeton drill core. The relative chronology is indexed to the Tr/J palynofloral boundary with a radiometric age estimate of 202 Ma and other parameters shown in first row. The interpolated values of position in cycle, depth, and age are quoted with a precision needed for internal consistency.

stable of the relevant astronomical periodicities [*Berger et al.*, 1992], we calculate a mean geomagnetic reversal rate of 1.88 m.y.$^{-1}$ for more than 30 m.y. of the Late Triassic. Reversal rates of 2.8 to 2.9 m.y.$^{-1}$ have been previously estimated from magnetostratigraphic studies of Carnian and Norian Tethyan marine sections by *Gallet et al.* [1992, 1993]. However, these authors noted that exclusion of less reliable polarity intervals defined by only single samples lowers these estimates of reversal rate to 1.8 to 1.9 m.y.$^{-1}$, values that are virtually identical to the reversal rate we estimate from the Newark GPTS (Figure 7).

In terms of correlation, the Tethyan polarity sequence for the Norian can be reasonably matched to the Newark GPTS [*Kent et al.*, 1995]. This correlation would require that Tethyan biozones, which are sometimes assumed to be of equal duration in chronostratigraphic applications, vary in duration by a factor of 2 or more. For the Carnian, correlation of the generally more fragmented and highly condensed polarity successions available from the Tethyan realm to the Newark GPTS is still not obvious [*Kent et al.*, 1995; *Gallet et al.*, 1996]. Confirmation of the Newark reversal pattern for the late Carnian (from E9n to E13r) has nevertheless been obtained in a ~3000-m-thick continental sedimentary section in the Dan River-Danville basin of North Carolina and Virginia located >600 km from the Newark Basin [*Kent and Olsen*, 1997].

There is no evidence in either the Tethyan sections or the Newark GPTS for a prominent interval of low relative reversal rate [*Johnson et al.*, 1995] or strong normal polarity bias [*Algeo*, 1996] at around the Triassic/Jurassic boundary. In the Late Triassic, the reversal rate actually tends to be higher in the 5 to 10 m.y. just prior to magnetozone E24n in the Newark GPTS (Figure 6a). Magnetozone E24n, which starts just below the Triassic/Jurassic boundary and encompasses the igneous extrusive zone and overlying sediments in the Newark basin, is of the order of 1000 m thick. This might make it the thickest polarity interval in the Newark sequence but not the longest because at least the exposed portion is less than 1 m.y. long on the basis of cycle stratigraphy and there are nine other polarity chrons in the Newark GPTS that are longer than

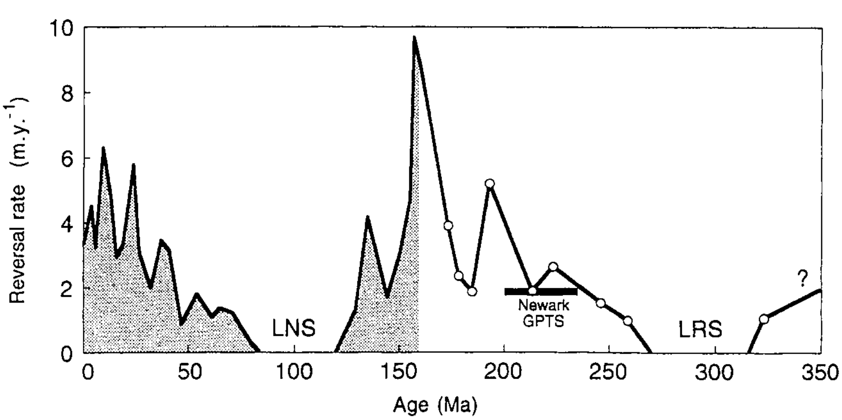

Figure 7. Geomagnetic reversal rate since 350 Ma [after *Gallet et al.*, 1992]. LNS is (Cretaceous) Long normal superchron and LRS is (Kiaman) Long reverse superchron. Interval from about 160 Ma to Present where reversal rate can be precisely estimated from marine magnetic anomalies is shaded. Individual magnetostratigraphic studies (open circles) provide reversal rate estimates for times prior to 160 Ma and in some cases are based on filtered subsets of data that are thought to be more reliable (see *Gallet et al.* [1992] for references and discussion). Reversal rate of 1.88 m.y.$^{-1}$ for Late Triassic determined in this paper is shown by solid horizontal bar.

1 m.y. (Table 1). The apparently short duration of the Hettangian (e.g., 3.8 m.y. [*Gradstein et al.*, 1995]) and the documentation of magnetic reversals by the Sinemurian if not the later part of the Hettangian in marine sediments of the Paris Basin [*Yang et al.*, 1996] further limit the possibilities for a significantly long polarity interval in the earliest Jurassic.

The earliest Jurassic (Hettangian) was not only an interval of predominantly normal polarity but evidently also a time of widespread igneous activity and thick accumulation of strata in the rift basins of the Atlantic margins [*McHone*, 1996; *Olsen et al.*, 1996b]. This suggests an alternative explanation for indications of an apparently low relative reversal rate and strong normal polarity bias at around the Triassic/Jurassic boundary; that is, paleomagnetic results from the Hettangian may simply be over-represented in paleomagnetic compilations such as those analyzed by *Johnson et al.* [1995] and *Algeo* [1996]. The timing between major changes in reversal rate over the Phanerozoic has long been recognized to be ~200 m.y., paced by the Cretaceous Long Normal, the Permo-Carboniferous (Kiaman) Long Reverse interval, and perhaps the Ordovician Polarity Bias interval [e.g., *McElhinny; 1971*; *Irving and Pullaiah*, 1976]. If an intervening Triassic/Jurassic or Early Jurassic polarity feature is an artifact of sampling bias, as we suspect, ~200 m.y. would remain the most significant time constant for long-term field behavior, presumably reflecting mantle control.

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