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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].

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

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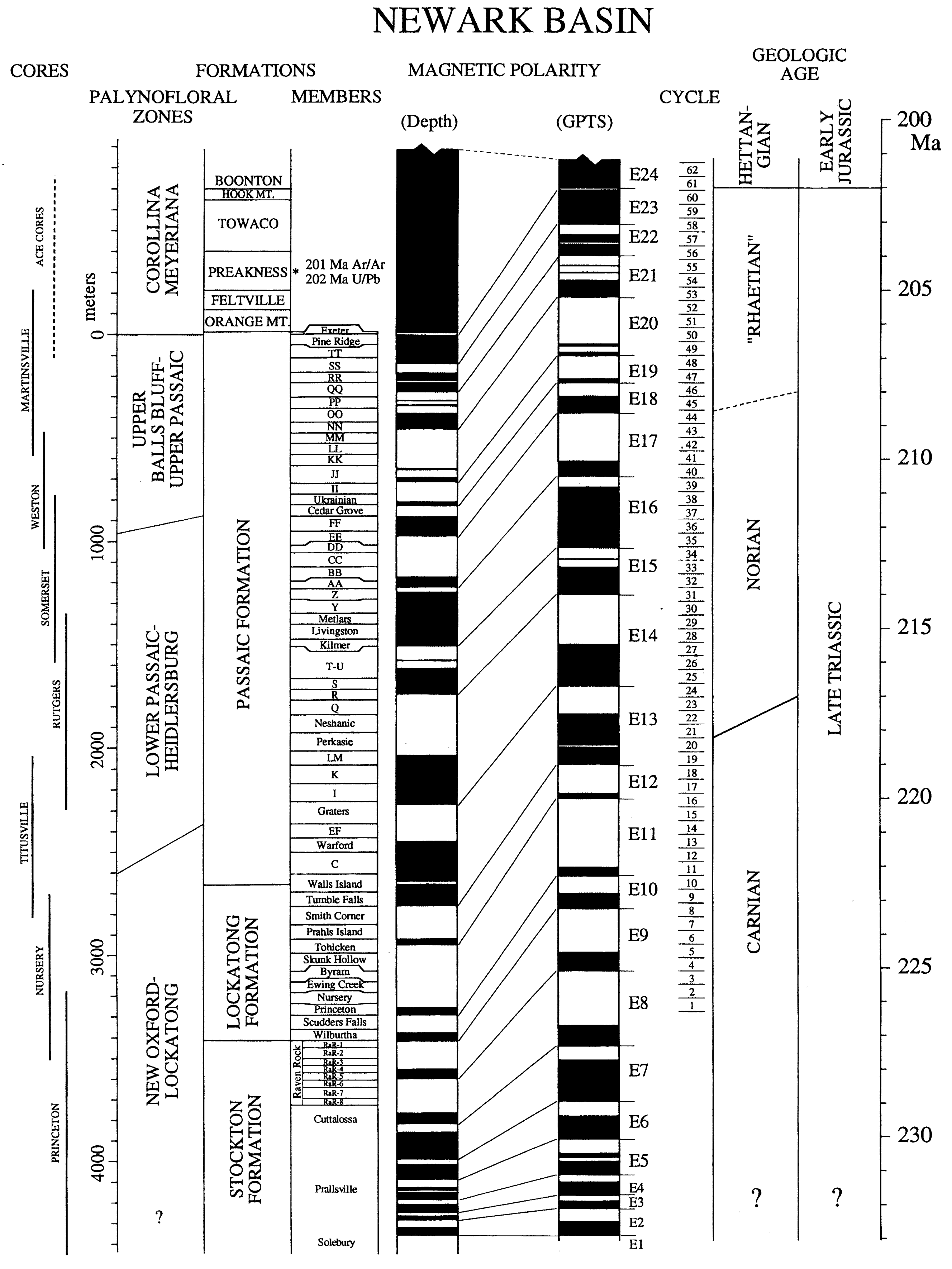
NEWARK BASIN
CORES
FORMATIONS
MAGNETIC POLARITY
GEOLOGIC AGE
PALYNOFLORAL ZONES
MEMBERS
CYCLE
(Depth)
(GPTS)
ACE CORES
MARTINSVILLE
WESTON
SOMERSET
RUTGERS
TITUSVILLE
NURSERY
PRINCETON
meters
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1000
2000
3000
4000
COROLLINA MEYERIANA
UPPER BALLS BLUFF-UPPER PASSAIC
LOWER PASSAIC-HEIDLERSBURG
NEW OXFORD-LOCKATONG
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BOONTON
HOOK MT.
TOWACO
PREAKNESS
FELTVILLE
ORANGE MT.
PASSAIC FORMATION
LOCKATONG FORMATION
STOCKTON FORMATION
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202 Ma U/Pb
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QQ
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Cedar Grove
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Graters
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Warford
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Walls Island
Tumble Falls
Smith Corner
Prahls Island
Tohicken
Skunk Hollow
Byram
Ewing Creek
Nursery
Princeton
Scudders Falls
Wilburtha
Raven Rock
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RaR-2
RaR-3
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1
HETTAN-GIAN
EARLY JURASSIC
"RHAETIAN"
NORIAN
CARNIAN
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.

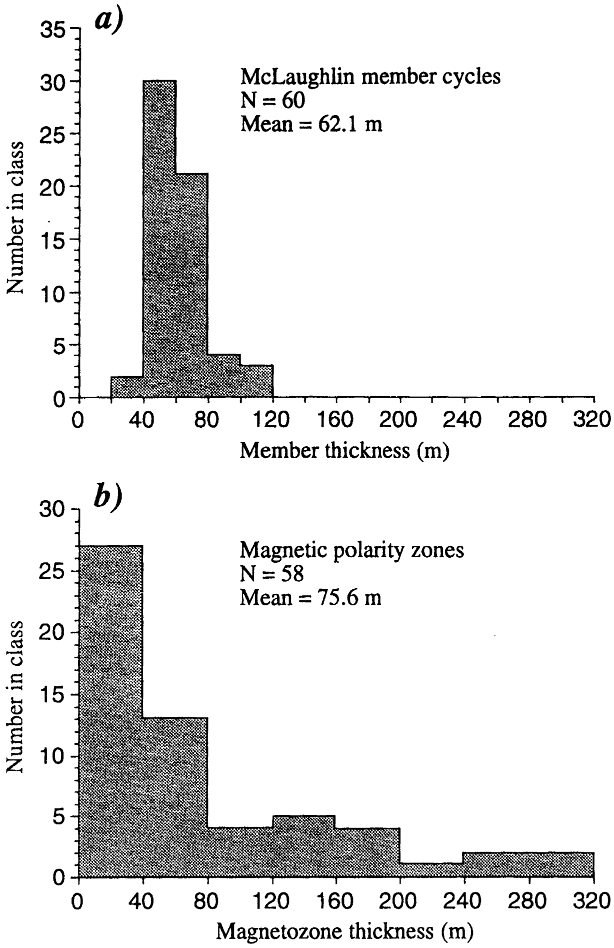

**Figure 2.** Histogram of thicknesses of (a) McLaughlin lithologic member cycles, and (b) magnetic polarity zones in upper Triassic sediments recovered in NBCP drill cores from Newark Basin section.

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

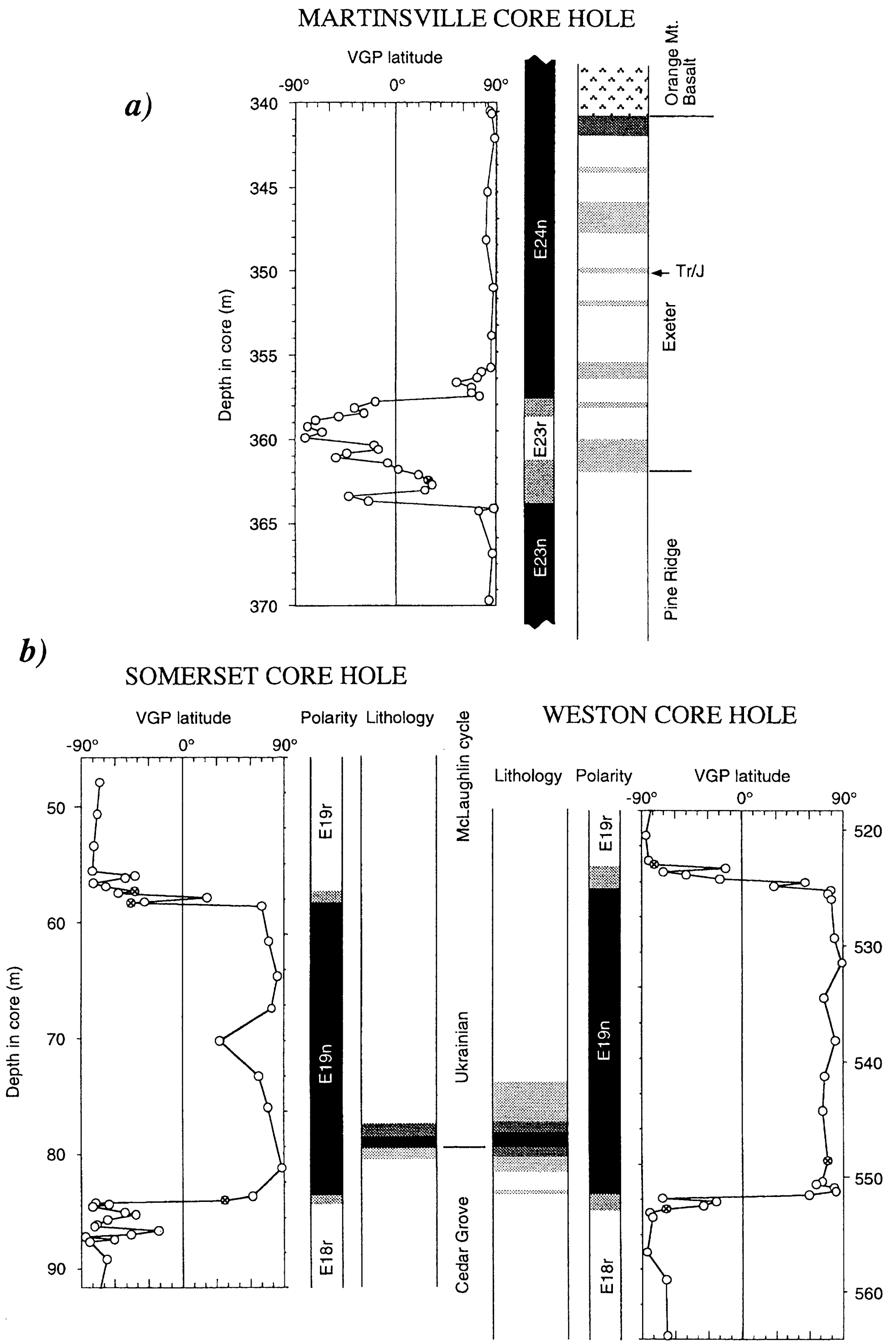

**Figure 3.** Polarity transition records for (a) magnetozone E23r (formerly E23n.1r) in the Martinsville drill core, just below the contact with the Orange Mountain Basalt, and (b) magnetozone E19n in the upper part of the Somerset drill core and the lower part of the Weston drill core which were correlated 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.