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Late Triassic-earliest Jurassic geomagnetic polarity sequence and paleolatitudes from drill cores in the Newark rift basin, eastern North America

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Abstract. Paleomagnetic study of about 2400 samples from nearly 7 km of core recovered at seven drill sites in the Newark continental rift basin of eastern North America provides a detailed history of geomagnetic reversals and paleolatitudinal motion for about 30 m.y. of the Late Triassic and earliest Jurassic (Carnian to Hettangian). Northward drift of only about 7° is recorded in the continental sediments and minor interbedded basaltic lavas in the basin, from 2.5° to 6.5° north paleolatitude in the Carnian and from 6.5° to 9.5° north paleolatitude over the Norian-"Rhaetian" and the early Hettangian. A total of 59 polarity intervals, ranging from about 4 m to over 300 m in thickness, have been delineated in a composite stratigraphic section of 4660 m. The lateral continuity and consistent relationship of lithological lake level cycles and magnetozones in the stratigraphically overlapping sections of the drill cores demonstrate their validity as time markers. A geomagnetic polarity timescale was constructed by scaling the composite section assuming that lithostratigraphic members in the predominant lacustrine facies represent the 413-kyr orbital periodicity of Milankovitch climate change and by extrapolating a sedimentation rate for the fluvial facies in the lower part of the section; a 202 Ma age for the palynological Triassic/Jurassic boundary was used to anchor the chronology based on published concordant radiometric dates linked to the earliest Jurassic igneous extrusive zone. Geomagnetic polarity intervals range from about 0.03 to 2 m.y., have a mean duration of about 0.5 m.y., and show no significant polarity bias. The cyclostratigraphically calibrated record provides a reference section for the history of Late Triassic-earliest Jurassic geomagnetic reversals. Correlations are attempted with available magnetostratigraphies from nonmarine sediments from the Chinle Group of the southwestern United States and marine limestones from Turkey.

Introduction

The global nature of geomagnetic polarity reversals has made magnetostratigraphy an essential tool for precise correlation between widely distributed sections of rocks of different lithological and biotic facies. The best documented history of geomagnetic polarity reversals is for the Jurassic to Recent and is based on the analysis of marine magnetic anomaly profiles from the global ocean [e.g., *Cande and Kent,* 1992; *Gradstein et al.*, 1994]. The relative spacing of polarity intervals is established from the anomaly patterns and is calibrated in time by correlation to magnetostratigraphic sections with biostratigraphy, radiometric dates, and now by cyclostratigraphy [e.g., *Shackleton et al.*, 1990; *Hilgen*, 1991]. Because of the absence of seafloor and hence marine magnetic anomalies, a geomagnetic polarity reference scale for pre-Jurassic time is much less well developed and requires long, continuous magnetostratigraphic sections with good chronostratigraphic control from the continents.

A very thick sequence of lacustrine and fluvial sediments is represented in the Newark Basin, one of the largest of a chain of Mesozoic rift basins that developed along the margin of eastern North America in the early stages of formation of the Atlantic Ocean [*Manspeizer*, 1988]. Deposition in the basin is now known to span much of the the Late Triassic to earliest Jurassic [*Cornet and Olsen*, 1985] and was punctuated only by a brief igneous intrusive and extrusive episode just after the Triassic/Jurassic boundary [*Olsen and Sues*, 1986; *Fowell et al.*, 1994] and dated at 201-202 Ma [*Sutter*, 1988; *Dunning and Hodych*, 1990]. The lacustrine sediments that constitute much of the Newark Basin section record climatically induced lake level variations reflecting Milankovitch orbital forcing [*Van Houten*, 1964; *Olsen*, 1986]. These climatic cycles constitute a basis for detailed lithostratigraphic correlation as well as chronological scaling.

Early paleomagnetic work on Newark Supergroup rocks focused on the igneous units and found mostly normal polarity magnetizations [e.g., *DuBois et al.*, 1957; *Opdyke*, 1961; *Smith and Noltmier*, 1979]. This contributed to the concept of a quiet or long normal polarity interval in the Late Triassic and Early Jurassic [*McElhinny and Burek*, 1971; *Perchesky and Khramov,* 1973; *Irving and Pullaiah*, 1976; *Haq et al.*, 1988]. More extensive sampling of the Newark Basin sedimentary section has revealed the presence of numerous polarity reversals [*McIntosh et al.*, 1985; *Witte and Kent*, 1989, 1990; *Witte et al.*, 1991]. The Newark Basin section thus provides an opportunity to obtain a cyclostratigraphically scaled, high-resolution timescale of

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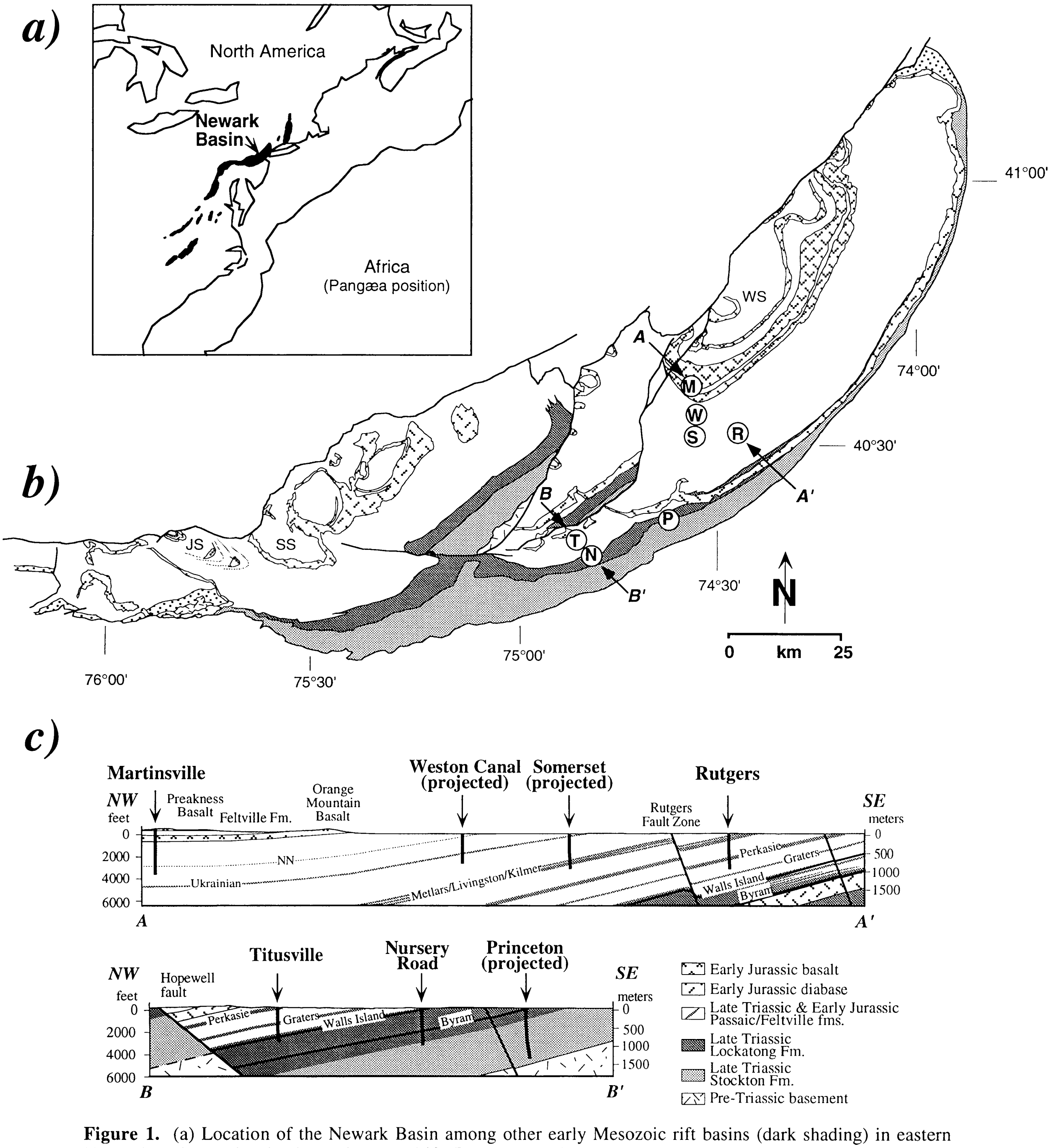

Figure 1. (a) Location of the Newark Basin among other early Mesozoic rift basins (dark shading) in eastern North America which is shown in a predrift (Pangea) continental configuration with respect to Africa. (b) Geological sketch map of the Newark Basin with the location of Newark Basin Coring Project drill sites indicated by the circled first letter of the site name. Other localities referred to in the text are WS, Watchung syncline; SS, Sassamansville syncline; JS, Jacksonwald syncline. (c) Cross sections showing positions of NBCP drill sites projected onto A-A' and B-B' of Figure 1b.

Late Triassic and earliest Jurassic geomagnetic polarity reversals. Outcrop exposure is, however, typically poor and discontinuous due to the low relief and urbanized setting of the basin. This difficulty was addressed by the National Science Foundation-sponsored Newark Basin Coring Project (NBCP) which resulted in the recovery of a virtually complete stratigraphic section through the thick continental rift basin sequence of central New Jersey from seven stratigraphically overlapping drill cores. The lithostratigraphy and cyclostratigraphy of the NBCP cores are described by *Olsen et al.* [1995] and *Olsen and Kent* [1995]. The paleomagnetism of the NBCP cores is reported here.

Geologic Setting and Coring

An extensive series of rift basins formed in eastern North America during the initial rifting of Pangea (Figure 1a). These rifts filled with thousands of meters of continental sediments, basalts, and diabase termed the Newark Supergroup [*Olsen*, 1978, 1980; *Froelich and Olsen*, 1984]. The Newark Basin, about 190 km long and up to 50 km wide, is the largest of the exposed Newark Supergroup basins. It is a half graben bound on the northwest by a set of predominantly normal faults, and is broken into five or so major, northwest tilted fault blocks whose hanging walls have folds with northwesterly trending axes [*Wheeler*, 1939; *Schlische*, 1992]. Subsequent erosion of these rotated fault blocks and folds, including about 2 km of section [*Roden and Miller*, 1991; *Steckler et al.*, 1993], provides surface or near-surface access of much of the Newark Basin section.

A stratigraphic section was obtained by drilling in the rift basin sequence of the eastern and southeastern parts of central New Jersey (Figure 1b). The section was assembled from an array of seven relatively shallow (~800 to 1200 m) continuously cored drill holes. The drill holes intersected overlapping stratigraphic intervals along two transects (Figure 1c) to avoid drilling through the Palisade sill, a thick igneous intrusive unit. The regional 5° to 15° northwest formation dip made the offset drilling strategy possible.

Six of the drill sites were cored in late 1990 to early 1991 by Amoco Production Company using a closed circulation diamond coring system; on-site core analysis was provided by their automated Geological Evaluation Modules. The seventh drill site was cored in early 1993 by the Longyear Drilling Company. For those sites needing continuous core from the surface, New Jersey state regulations required the practice of drilling a shallow hole (well 2) from the surface to about 100 m to recover the cased interval in the immediately adjacent deep hole (well 1) that was cored from about 100 m to total depth. The 12 wells in the order cored were the Rutgers 1 and 2, Somerset 1 and 2, Titusville 1 and 2, Martinsville 1, Nursery 1, Princeton 1 and 2, and Weston 1 and 2. Correlation of wells 1 and 2 is unambiguous, and all the drill core sites are henceforth referred to by the locality name without further distinction of well number. Core depth was given by the drillers in decimal feet from the surface and marked directly on the core. The primary measurements are indexed to this footage which has been converted to metric units in reporting the stratigraphic results.

A total of 6770 m of 6.3-cm-diameter core was drilled at the seven coring sites (Table 1), including about 25% redundancy between the stratigraphically overlapping drill cores. Core recovery overall was virtually complete (better than 99% of the cored intervals), with only a small amount of undergauge and broken core. Supporting information was obtained from a full suite of slimhole geophysical logs [*Goldberg et al.*, 1994]; the most pertinent logging data for the present study are the hole deviation survey and dipmeter logs which allow restoration of the drill core to the vertical and the tilted beds to the paleohorizontal frame of reference.

The cores span most of the Stockton Formation, all of the Lockatong Formation, Passaic Formation, and Orange Mountain Basalt, and practically all of the Feltville Formation (Figure 2). The stratigraphy of the Newark Basin used here follows the nomenclature of *Olsen* [1980] and is described fully by *Olsen et al.* [1995]; sedimentary facies and depositional environments are discussed in more detail by *Smoot* [1991]. The Stockton Formation is the lowest stratigraphic unit and consists of buff-colored to red arkosic sandstones and siltstones of predominantly fluvial facies. The Lockatong Formation is dominated by gray to black shales with minor red siltstones and mudstones, interpreted as a relatively deep-water lacustrine facies. Red siltstones and mudstones become progressively more dominant in the overlying Passaic Formation and denote an overall shallowing lacustrine facies, although distinctive gray to black shale interbeds are still present. The Orange Mountain Basalt, the lowermost of the igneous extrusive units in the Watchung syncline, is a quartz-normative tholeiitic basalt consisting of three major lava flows. The overlying Feltville Formation shows a reversal in the upward shallowing/drier conditions of the Passaic and Lockatong Formations and consists of interbedded red and gray to black shales. The succeeding basaltic flows and sedimentary units of the Watchung syncline (Preakness Basalt, Towaco Formation, Hook Mountain Basalt, and Boonton Formation) were previously recovered in a series of shallow core holes by the Army Corp of Engineers [*Fedosh and Smoot*, 1988].

The sedimentary facies of the lacustrine Lockatong, Passaic and Feltville Formations have several orders of cyclic

Table 1. Newark Basin Coring Project Drill Site Parameters and Inventory of Paleomagnetic Samples by Dominant Lithology and Components Isolated

		Rejected		Accepted	
"Lithology"	*N*	A or B	C	*n*	*n/N*%
Martinsville (40°37'09"N, 74°34'22"W, 1184 m Cored)					
Red	370	19	11	340	92
Basalt	70	-	0	70	100
Weston (40°32'33"N, 74°33'49"W, 789 m Cored)					
Red	260	1	13	246	95
Somerset (40°30'31"N, 74°33'58"W, 914 m Cored)					
Red	330	6	15	309	94
Rutgers (40°32'33"N, 74°26'00"W, 940 m Cored)					
Gray	2	0	0	2	100
Red	338	3	1	334	99
Total	340	3	1	336	99
Titusville (40°19'35"N, 74°51'02"W, 916 m Cored)					
Gray	85	1	24	60	71
Red	278	10	20	248	89
Total	363	11	44	308	85
Nursery (40°18'03"N, 74°49'27"W, 914 m Cored)					
Gray-black	197	29	58	110	56
Red-purple	127	10	33	84	66
Total	324	39	91	194	60
Princeton (40°22'09"N, 74°36'49"W, 1116 m Cored)					
Gray-black	54	10	23	21	39
Red/pink/buff	351	85	59	207	59
Total	405	95	82	228	56
All Seven Sites (6773 m Cored, >99% Recovered)					
Grayish	338	40	105	193	57
Reddish	2054	134	152	1768	86
Gray+Red	2392	174	257	1961	82
Basalt	70	-	0	70	100
Total	2462	174	257	2031	82

Number of paleomagnetic samples measured, *N*, compared to those rejected on basis of poor overprint (A or B component) or characteristic (C component) magnetizations, and those accepted (*n*) for magnetostratigraphic and paleopole analyses. Generalized lithologies described as basalt or by color of sediment.

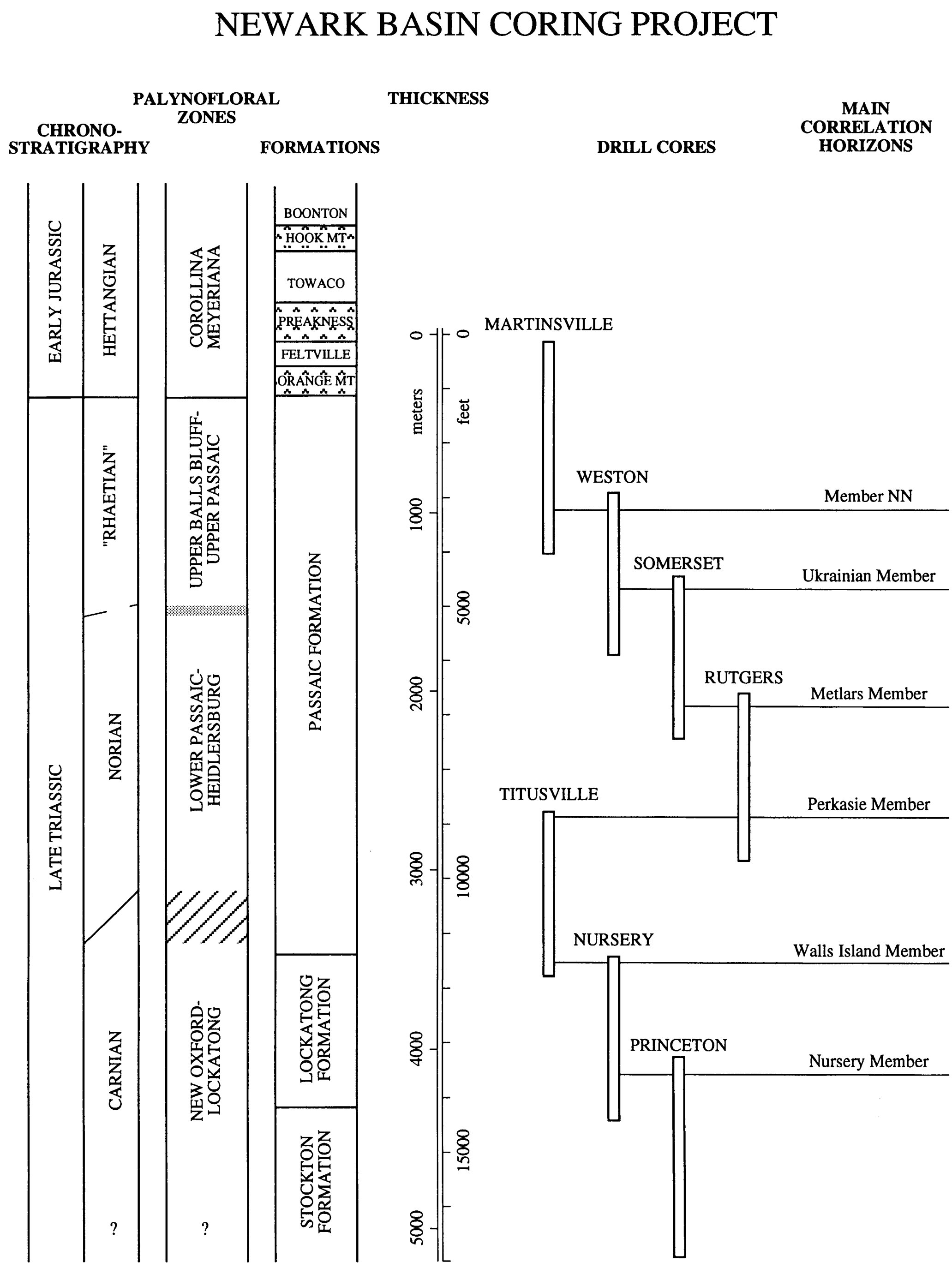

Figure 2. Stratigraphy of the Newark Basin and the section recovered by coring at the seven NBCP sites and a series of Army Corps of Engineers (ACE) cores [*Fedosh and Smoot,* 1988]. Thickness scale is the nominal aggregate length of stratigraphically overlapping NBCP drill cores linked by main correlation horizons. Palynofloral zonation is from *Cornet* [1977, 1993] and *Cornet and Olsen* [1985].

variation that are interpreted to represent climatically-induced changes in lake level reflecting Milankovitch orbital forcing [*Van Houten*, 1964; *Olsen*, 1986; *Olsen and Kent*, 1995]. The fundamental sedimentary variation is referred to as the Van Houten cycle, which is recognized on a stratigraphic scale of 3 to 6 m in the NBCP cores and consists of three divisions (Figure 3a). Division 1 is a relatively thin unit, generally massive at its base and becoming better bedded upward as the density of desiccation cracks and/or tubes (root or burrows) decreases. Division 2 has the best developed bedding in the cycle, commonly consisting of gray or black fissile mudstone. Division 3 becomes more massive upward by an increase in the frequency of desiccation cracks and/or tubes. Divisions 1 and 3 may be gray, purple, or red with lighter colors

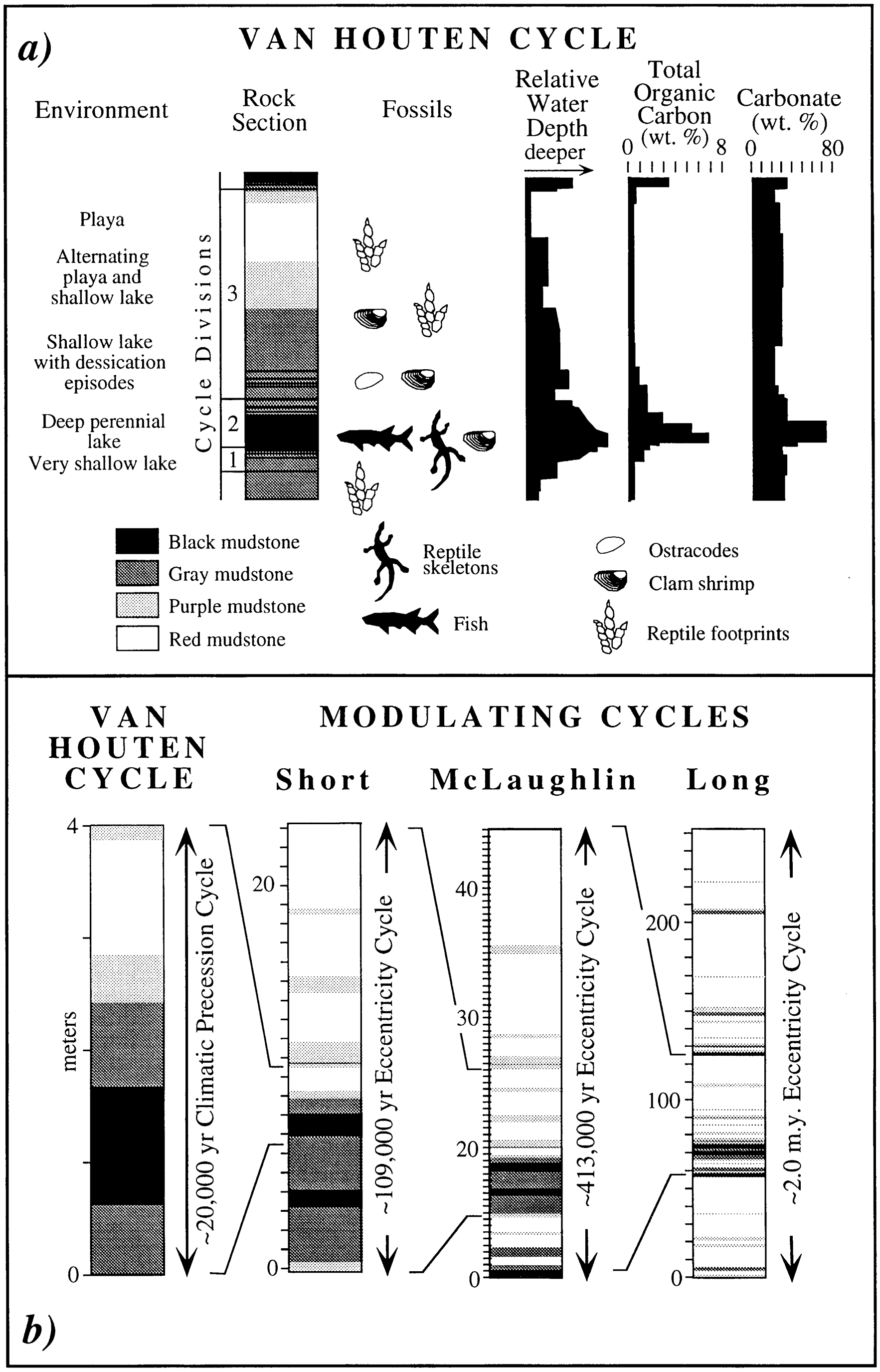

Figure 3. (a) Diagrammatic representation of a Van Houten cycle, showing the succession of lacustrine facies in the three divisions of the cycle and their paleoenvironmental interpretation. (b) Relationship of the Van Houten cycle and the short, McLaughlin, and long modulating cycles; nominal length scales and timescales are as interpreted in the NBCP drill cores.

predominating, while division 2 can be red, purple, gray, or black with darker colors being common. The tripartite division of the Van Houten cycle thus represents a deepening-high stand-shallowing sequence in relative lake level. Variations in Van Houten cycles in the NBCP cores are described in more detail by *Smoot and Olsen* [1994].

The expression of Van Houten cycles in terms of development of lamination and drab to black colors is modified by three orders of modulating cycles termed the short, intermediate or McLaughlin, and long cycles (Figure 3b). In the "peaks" of each of these modulating cycles, Van Houten cycles tend to be dominated by drab and dark colors; division 2 can be thick, black, and finely laminated, suggesting wetter climates and relatively deeper lakes. In the "troughs" of the modulating cycles, the Van Houten cycles tend to be mostly red; division 2 is usually red, purple, or gray fissile mudstone,