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Tectonic, Climatic, and Biotic Modulation of Lacustrine Ecosystems—Examples from Newark Supergroup of Eastern North America

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Rift-related early Mesozoic lacustrine strata of the Newark Supergroup provide a background for exploration of general concepts of lacustrine paleoecology and stratigraphic architecture. The large-scale tripartite sequence of depositional environments (i.e., fluvial basal part, deep lacustrine middle part, and shallow lacustrine or fluvial upper part), commonly seen in lacustrine deposits, including the Newark, can be quantitatively modeled as the result of relatively simple interaction between basin filling and subsidence. Whereas tectonic processes produced the rifts and the maximum depths of the lakes they contain, high-frequency fluctuations in the depths of rift lakes are largely controlled by climate. Milankovitch-type climatic cycles caused by variations in the Earth's axis and orbit produce lake-level cycles with periods of 21, 41, 100, and 400 k.y. The magnitude and mode of these lake-level changes are governed by position within the climate system and by orography.

Three major classes of lacustrine facies complexes are recognized in the Newark Supergroup. These are, in order of increasing overall dryness, the Richmond, Newark, and Fundy types. Each is characterized by different suites of highstand and lowstand deposits, different sedimentary cycle types, and different amounts of organic carbon-rich rocks. Organic-carbon content of the strata is largely a function of ecosystem efficiency, which, in turn, responds to lake depth. Finally, the long-term trends in evolution of bioturbators must be taken into account because they affect not only the carbon cycle and oxygen state within lakes but also our ability to interpret the metabolic state of ancient lake systems.

INTRODUCTION

Triassic and Lower Jurassic lacustrine rocks of the Newark Supergroup of eastern North America (Figure 1) were deposited in a long chain of rift valleys for about 30 m.y. prior to the breakup of Pangea. They comprise one of the world's largest examples of fossil lacustrine systems and provide a rich environment for examining macroscopic controls on lacustrine ecosystem development and evolution. This paper outlines the major themes of Newark Supergroup lacustrine ecosystems and their relation to lake systems in general.

GEOLOGICAL CONTEXT

Newark Supergroup deposits (Olsen, 1978; Froelich and Olsen, 1984) occupy a series of half-grabens exposed along the eastern Appalachian orogene from Nova Scotia to South Carolina. In cross section each half-graben is bounded on one side by a series of major basinward-dipping faults (the border fault system) and on the other by a gently dipping, more diffusely deformed floor of hanging-wall basement rocks with some synthetic as well as antithetic faults (Figure 2). In longitudinal section the basins comprise gentle synforms. Basins tend to be linked together into

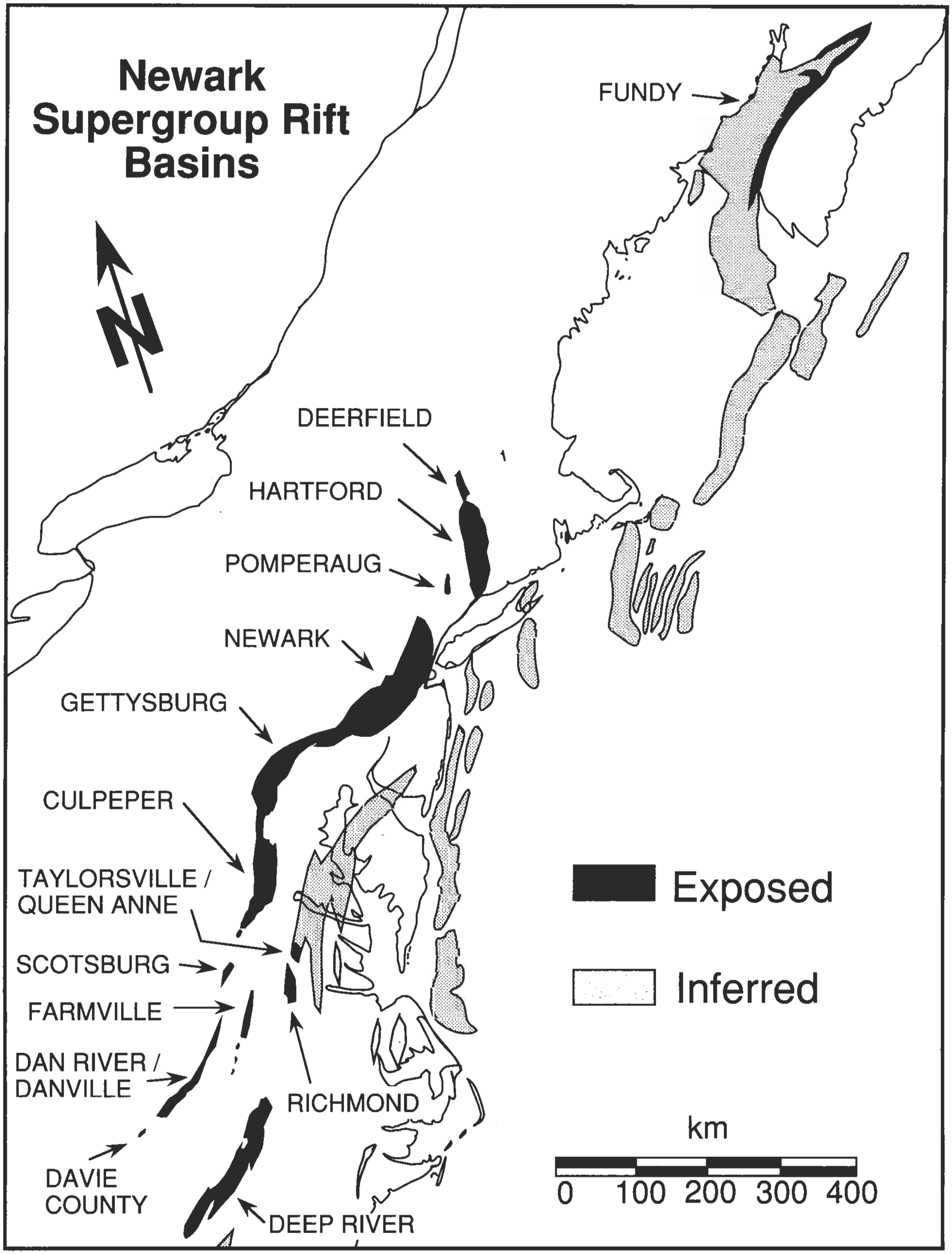

Figure 1. The Newark Supergroup of eastern North America. Adapted from Schlische and Olsen (1990). Note that the Fundy, Newark, Gettysburg, Culpeper, Dan River/Danville, Davie County, Farmville, Richmond, and Taylorsville/Queen Anne basins all have border faults on the west sides of the basins, and the Deerfield, Hartford, Pomperaug, and Deep River basins have border faults on the east sides of the basins.

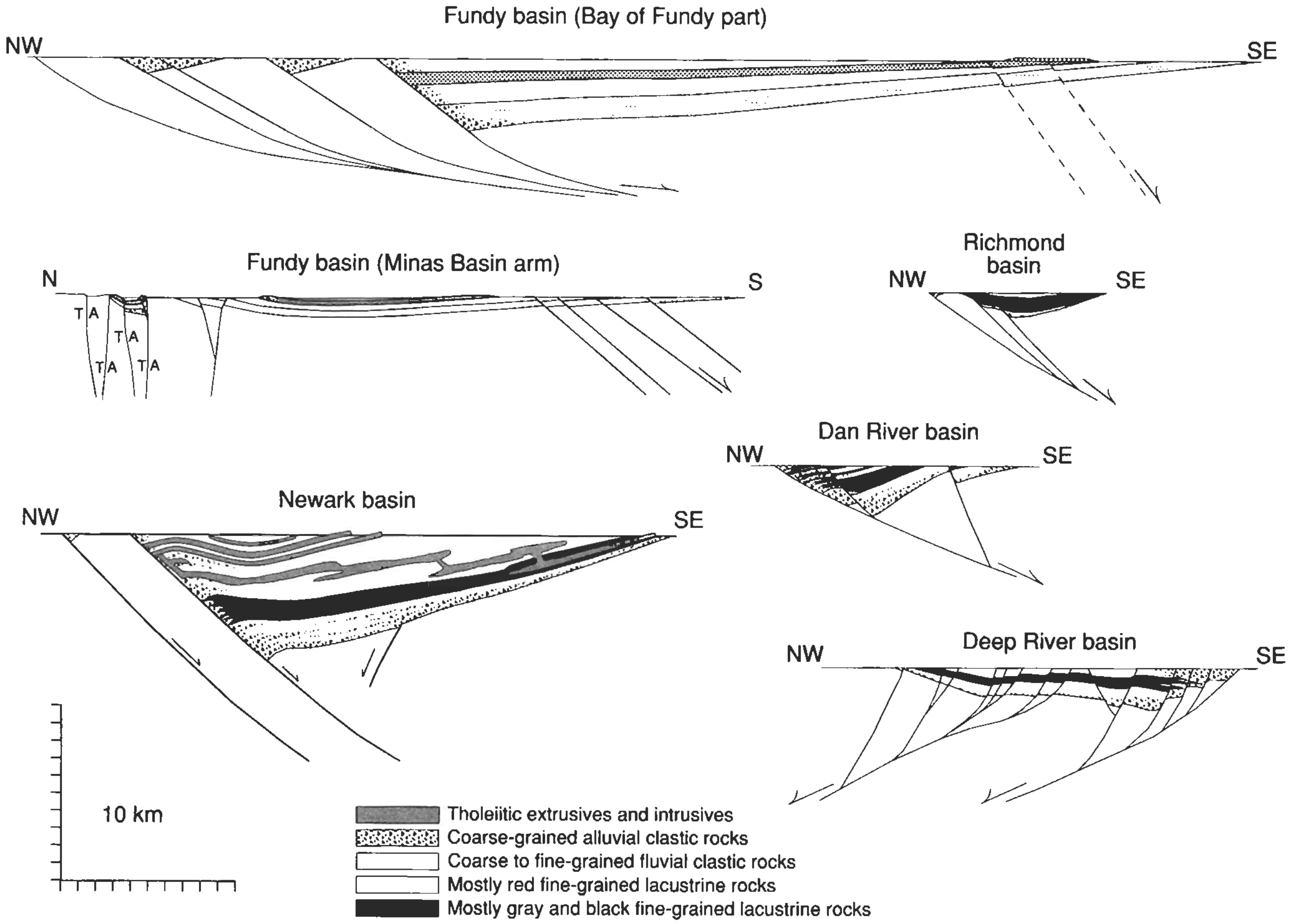

Figure 2. Cross sections of selected Newark Supergroup basins (see Figure 1 for locations). Note half-graben shape of all basins except the Minas basin arm of the Fundy basin, which lies along the largely strike-slip part of the basin where it trends east-west. Cross sections adapted from the following: Fundy basin (Olsen and Schlische, 1990); Newark basin (Schlische and Olsen, 1990); Dan River and Deep River basins (Olsen et al., in press); Richmond basin, original.

basin-subbasin complexes with their border fault systems all on the same side (e.g., the Newark-Gettysburg-Culpeper system) (Figure 1). These fault systems appear to be discrete, reactivated Paleozoic compressional faults (Ratcliffe and Burton, 1985; Ratcliffe et al., 1986). Thus, Newark Supergroup rifts differ substantially from east African rifts, whose subbasins tend to link with opposing border-fault systems that do not closely follow preexisting structures (Reynolds and Schlische, 1989).

Strata within the half-graben dip toward the border fault system and generally thicken toward it. Available and proprietary seismic profiles and outcrop data (Anderson et al., 1983; Olsen et al., 1989; Schlische and Olsen, 1990) suggest onlap of successively younger strata onto hanging-wall basement both transversely and longitudinally (Figure 2). In addition, most basins are cut by major internal faults, and transverse folds are present with their greatest amplitudes expressed in the hanging walls adjacent to most major faults (Schlische and Olsen, 1988). At least some internal faulting and folding appears to be synchronous with deposition (Schlische and Olsen, 1988; Olsen et al., 1989). All the exposed basins are deeply eroded, and major sections of basin fill have been removed since the Middle Jurassic.

STRATIGRAPHY AND MAJOR DEPOSITIONAL PATTERNS

Newark Supergroup basins show two fundamental depositional patterns (Schlische and Olsen, 1990). The first is fluvial, formed in a hydrologically open basin and characterized by (1) basinwide channel systems; (2) large- to small-scale lenticular bedding; (3) conglomeratic intervals that can span the basin; (4) paleocurrent patterns that are often axial or that are dominated by one direction across the basin, indicating through-going drainage; and (5) absence of evidence for large lakes, although some pond or paludal deposits have been found. The second pattern is lacustrine and fits accepted criteria for a hydrologically closed-basin model. According to Smoot (1985), these criteria include (1) systematic increase in grain size toward all basin boundaries, (2) paleocurrent patterns away from the basin's borders, (3) local provenance of coarse-grained strata near basin margins, (4) presence of evaporites or evaporite crystal casts, and (5) cyclicity of fine-grained sedimentary rocks in the central basin. Cyclical lacustrine beds have considerable lateral continuity (Olsen, 1988), and basin-marginal areas can be dominated by deposits of lake-margin fluvial and deltaic sequences and alluvial fans. Within a basin these two generalized depositional systems have considerable persistence through time and are the largest scale stratigraphic elements (Figure 3).

Given these two depositional modes, Newark Supergroup basins tend to display a gross tripartite stratigraphy (Figure 3), consisting of a basal fluvial interval overlain by a deeper water lacustrine interval in which inferred lake depth generally decreases upsection, which in turn is overlain by a shallower water lacustrine to fluvial interval. This is a common pattern in many nonmarine basins (Lambiase, this volume). Southern Newark Supergroup basins (Deep River, Dan River, Farmville, Richmond, and Taylorsville; Figures 1, 3) contain only Triassic deposits. The northern Newark basins (Culpeper, Gettysburg, Newark, Pomperaug, Hartford, Deerfield, and Fundy; Figures 1, 3) also contain Lower Jurassic sequences that show an abrupt return to deeper water lake environments followed by a slow shoaling upward. These Lower Jurassic sequences are interbedded with thick, tholeiitic lava flows. Lambiase (this volume) refers to the northern Newark basins as dual-cycle basins.

BASIN EVOLUTION

Lakes exist for two reasons—(1) a deficit between the sediment supply to a basin and the volume created by subsidence, leading to a basin with a perched outlet; and (2) a surplus in supply of water to the basin over losses through evaporation and outflow. The balance among supplied sediment, basin growth, and outlet erosion determines the maximum possible depth and area of the lake basin (Figure 4). According to Schlische and Olsen's (1990) mass-balance models, which are based on uniform rift-basin subsidence and sediment supply with no outlet erosion, if the tectonic subsidence rate is slow enough or the rate of sediment supply is high enough, an extensional basin initially will fill with fluvial sediment, and excess sediment and water will leave the basin. As the basin continues to subside, the same sediment volume will spread over an increasingly larger surface area. At some point the volume of sediment will just fill the basin; thereafter, a sediment-supply deficit occurs, and a lake basin forms. Sedimentation rate then will show a hyperbolic decrease through time, and the depth of the lake that could fill the basin (maximum possible lake depth) correspondingly will increase (Figure 4). After a brief period of exponential increase in maximum possible lake depth, the realized lake depth will slowly and hyperbolically decrease through time because the volume of water entering the basin is finite and reaches equilibrium with evaporation and seepage. If sediment supply is relatively low or subsidence rate relatively high, the basin will begin as lacustrine and remain so, with an ever increasing disparity between outlet position and sediment surface. Under conditions of uniform subsidence and sediment supply, this process is sufficient to produce the tripartite divisions of the Newark Supergroup and other extensional basins.

The aforementioned internal onlap pattern seen in Newark Supergroup basins, as well as other extensional basins (see compendium in Schlische and Olsen, 1990), shows that depositional surface area did increase through time, even during times of fluvial (open basin) deposition. This growth suggests progressive collapse of the hanging wall and migration of the hanging-wall hinge line away from the hanging wall cutoff. According to widely used volume- or area-balancing models of extension over a detachment (Gibbs, 1983; Groshong, 1989), this increasing area of subsidence should be balanced by decreasing rate of subsidence over the basin as a whole to conserve volume. Under these assumptions and uniform extension, subsidence rate would decrease in time, and Schlische and Olsen's basin-filling model could not produce the change from fluvial (open) to lacustrine (closed basin) conditions, although a decease in sedimentation rate still would be observed. Because this basin-filling model is based on the simplest geometrical assumptions, either the assumptions of the balancing models are incorrect, or extension rates changed during development of the basin. If extension rates increased early in basin history and volume-balancing models are correct, then the subsidence rate in the basin could have been approximately constant or could even have increased through time; thus, the change from fluvial to lacustrine deposition is still predicted by Schlische and Olsen's basin-filling model.

An abrupt increase in subsidence rate should increase basin asymmetry and temporarily decrease depositional and lake surface areas, thus increasing sedimentation rate and maximum lake depth (Schlische and Olsen, 1990). Accordingly, an earliest Jurassic increase in subsidence rate due to an increase in extension rate could have led to the stratigraphic patterns seen in northern Newark basins, as well as the extrusion of voluminous lava flows (Schlische and Olsen,1990; Olsen et al., 1989).

The along-strike linkage of several Newark Supergroup basins suggests the possibility of filling relays along a chain of subbasins, as described by

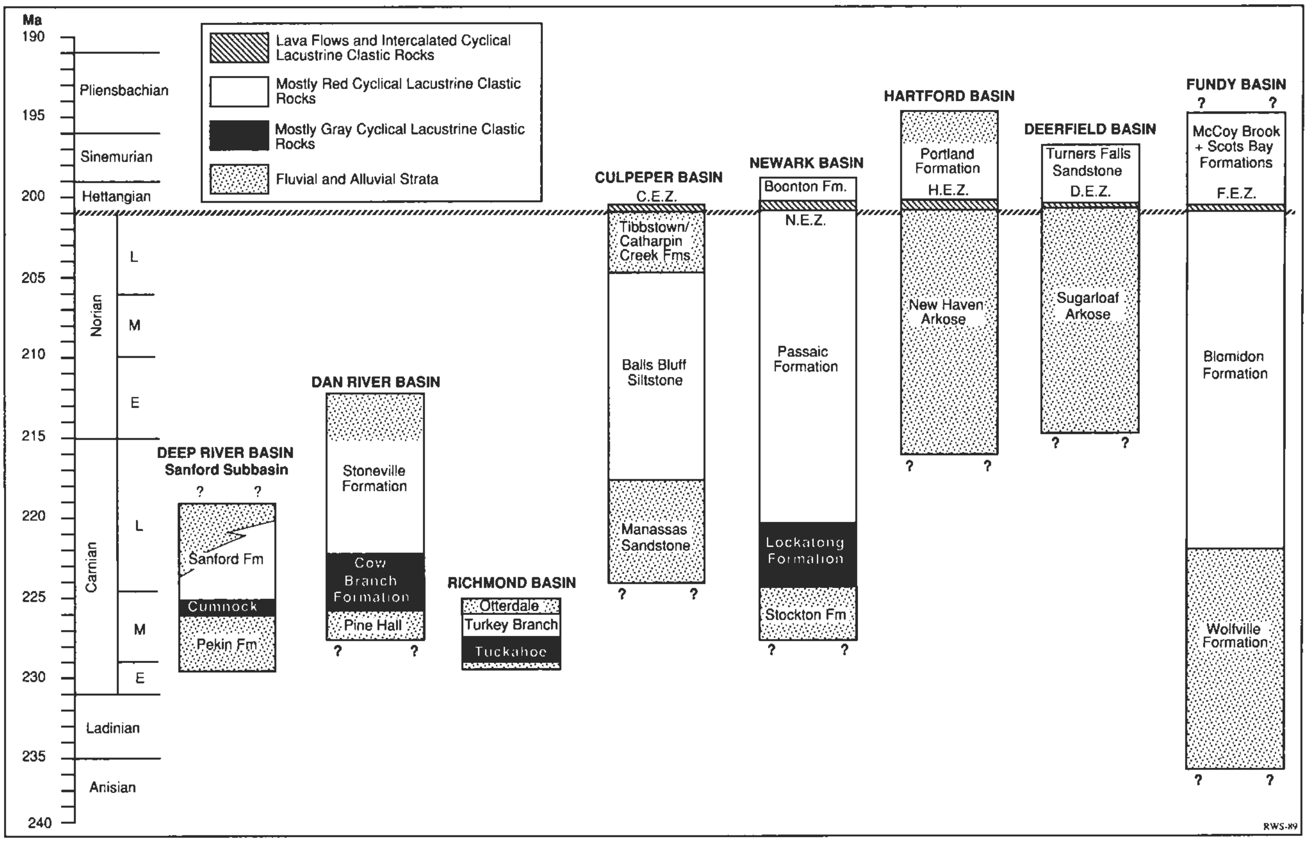

Figure 3. Correlation and facies types in Newark Supergroup basins (from Olsen et al., 1989). Abbreviations: CEZ, Culpeper basin extrusive zone; NEZ, Newark basin extrusive zone; HEZ, Hartford basin extrusive zone; DEZ, Deerfield basin extrusive zone; FEZ, Fundy basin extrusive zone.

Lambiase (this volume). Such a relationship is, in fact, supported by differences in timing between the onset and cessation of lacustrine deposition in the subbasins of the Deep River basin (described in Olsen et al., in press) and the Newark-Gettysburg-Culpeper basin system (Olsen et al., 1989). These possibilities have yet to be explored in detail, however.

CONTROL OF WATER IN THE LAKE

Water is needed in a basin to produce a lake; thus, whether or not a lake exists depends as much on climate and groundwater as on basin morphology. Recent studies of Quaternary climate and global climate models show that climate is not static, even in the tropics (Hays et al., 1976; Rossignol-Strick, 1983; Street-Perrott, 1986; Kutzbach, 1987). The history of a single lake is thus decoupled, in part, from the history of its basin.

Three broad types of lacustrine facies complexes can be recognized in the Newark Supergroup, each of which is characterized by magnitude and frequency of lake-level change. These I call the Newark-type, Richmond-type and Fundy-type lacustrine facies complexes. The most common is the Newark-type (Figure 5), in which water inflow was closely balanced by outflow. This type of facies complex occurs in the Dan River/Danville, Culpeper, Gettysburg, Newark, Pomperaug, Hartford, and Deerfield basins. Changes in precipitation resulted in dramatic changes in lake level from perhaps 200 m or more in depth to complete exposure, producing repetitive sequences of sedimentary cycles called Van Houten cycles (Figure 6) (Olsen, 1984b, 1986). These cycles range from about 1.5 to 35 m thick, and Milankovitch-type climate changes appear to have been their cause. Based on Fourier analyses of dozens of sections from several basins (one example in Figure 7), Van Houten cycles appear to have been under the control of the precession cycle of about 21 k.y., and clusters of Van Houten cycles make up larger cycles under the control of the eccentricity cycles of about 100, 400, and 2000 k.y. (Olsen, 1986; Olsen et al., 1989). A small effect of the obliquity cycle (41 k.y.) also is apparent.

Drastic changes in lake level apparently inhibited the buildup of high-relief sedimentary features (other than alluvial fans) within the basin both by wave action during transgression and regression and by the brief time the water was deep. Consequently, lacustrine strata are characterized by extreme lateral

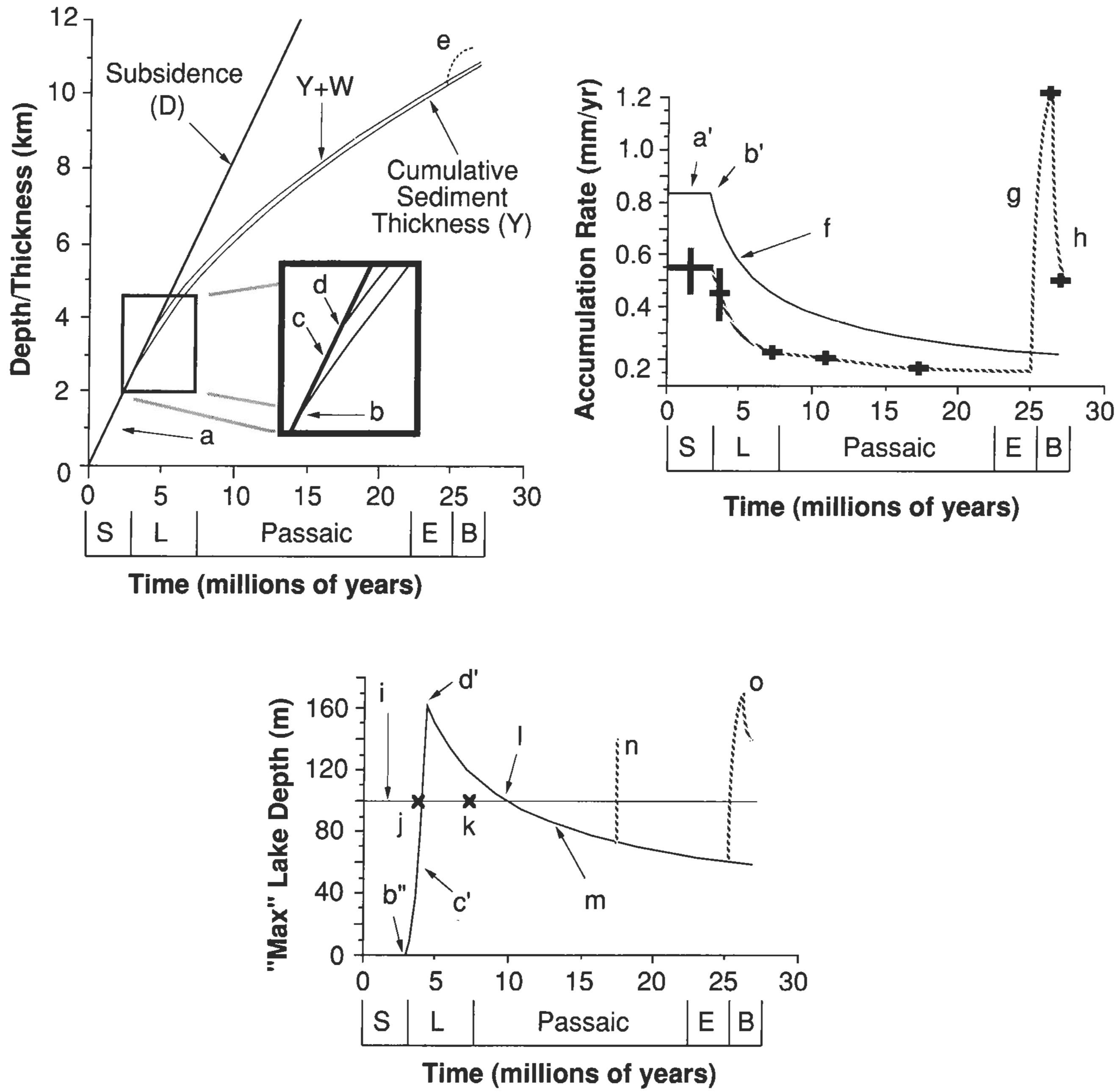

Figure 4. Predictions of the Schlische and Olsen (1990) model of stratigraphic development, assuming constant sediment input and constant subsidence (solid lines), compared to data from the Newark basin (dotted lines and crosses). Model is based on full-graben geometry but is parameterized for Newark basin. Y + W curve represents lake height above basin floor. Abbreviations: a, filling equals subsidence, resulting in fluvial sedimentation, with accumulation rate (a′) equal to subsidence rate; b, b′, and b″, onset of lacustrine deposition and sedimentologic closure; c and c′, rapid increase in lake depth as depositional surface subsides below hydrologic outlet; d and d′, deepest model-predicted lake and onset of hydrologic closure; e, major deviation from cumulative thickness curve during Early Jurassic; f, model-predicted hyperbolic decrease in accumulation rate; solid crosses represent data on accumulation rates from cyclical lacustrine strata from scattered outcrops; shaded cross represents estimated accumulation rate in fluvial Stockton Formation; g, anomalously high accumulation rate in extrusive zone, a deviation from model predictions; h, decreasing accumulation rate in Boonton Formation; i, 100-m minimum depth for formation of microlaminated sediment; j, actual first occurrence of microlaminated sediment; k, actual last occurrence of microlaminated sediment in lower Passaic Formation; l, predicted last occurrence of microlaminated sediment; m, slow decrease in lake depth; n, anomalous "superwet" climatic anomaly; o, anomalously deep Jurassic lakes. S, Stockton Formation; L, Lockatong Formation; E, Newark basin extrusive zone; B, Boonton Formation.

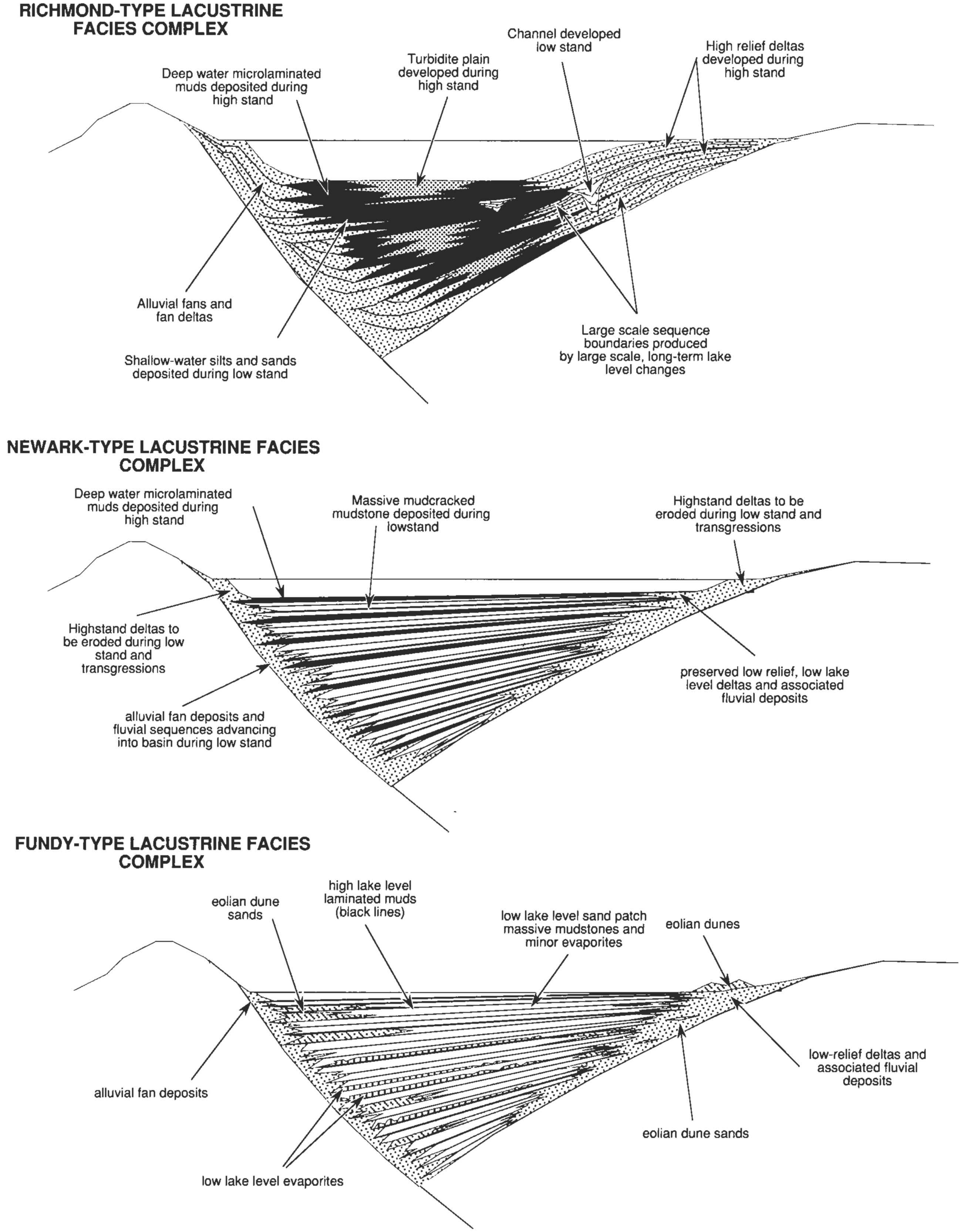

Figure 5. Idealized types of lacustrine facies complexes in Newark Supergroup. Note that no historical trend through the basin history is shown.

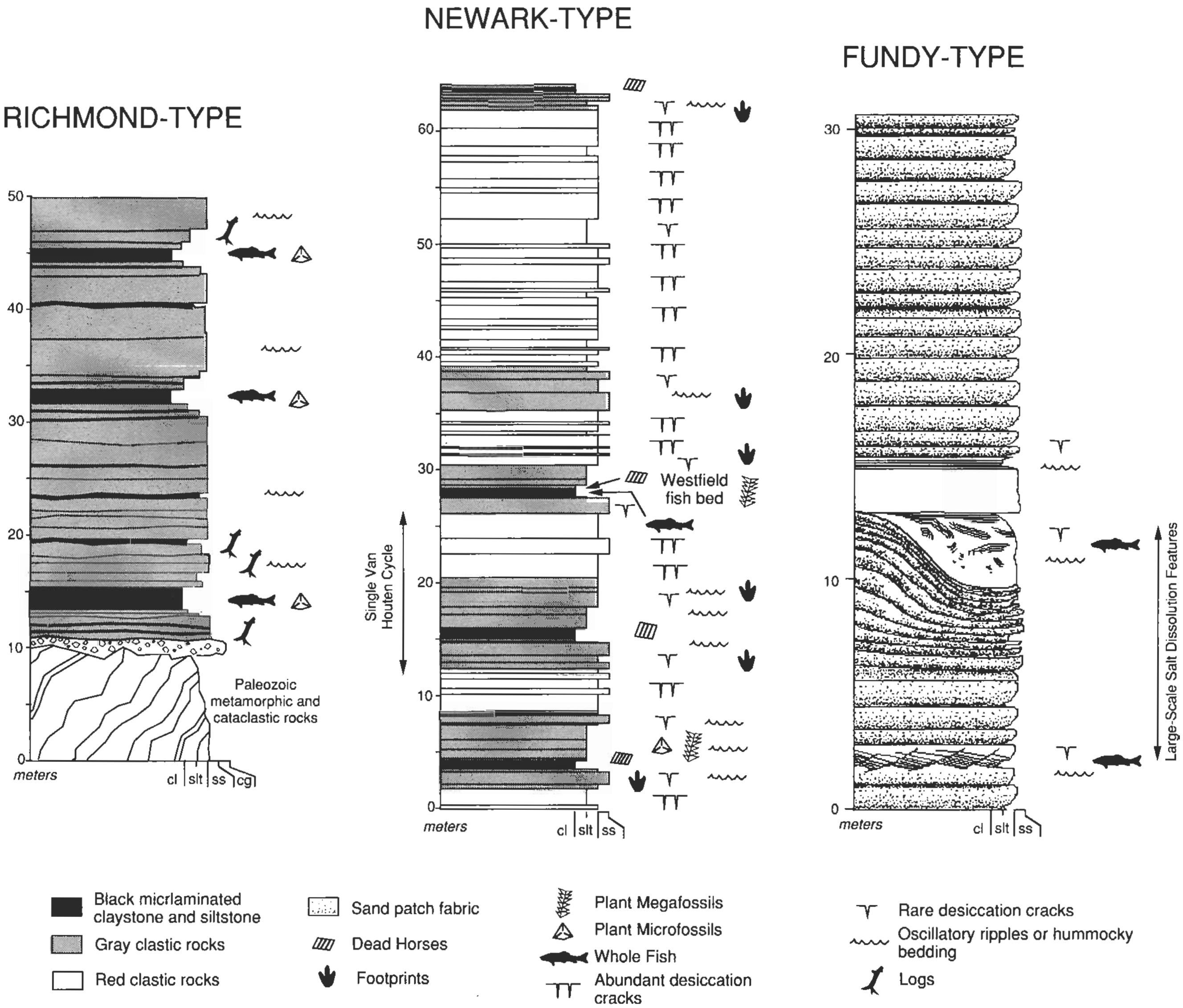

Figure 6. Comparison of sequences representative of the Richmond, Newark, and Fundy types of lacustrine facies complexes, illustrating repetitive sedimentary cycles (Van Houten cycles). Measured sections are from the following locations: Richmond type, Vinita Beds of Richmond basin (early Carnian), exposed at Boscobel Quarry, Manakin, Virginia; Newark type, middle East Berlin Formation (Hettangian) of Hartford basin, intersection of Routes 15 and 72, East Berlin, Connecticut (adapted from Olsen et al., 1989); Fundy type, lower Blomidon Formation, cliff outcrop at Blomidon, Nova Scotia (adapted from Olsen et al., 1989).

continuity and by a tendency for coarse-grained sediment to be absent from deeper water facies and restricted to basin margins (Olsen, 1985; Olsen et al., 1989). Large-scale sequence boundaries and large deltas apparently are absent from the main basin fill. In addition, although many Van Houten cycles contain thick, organic-rich deep-water units, the ratio of organic-rich to organic-poor units is very low. No close modern analogs to the exaggerated lake-level fluctuations seen in the Newark-type lacustrine facies complex apparently are known. However, apart from dramatic structural differences, the sediments of Lake Turkana (e.g., Cohen, 1989), among all east African rift lakes, appear to be most similar to the Newark-type complex during its intermediate water depths.

The Richmond-type lacustrine facies complex is less common and is known for certain only in the Richmond and Taylorsville basins (Figures 5, 6). To date, this lacustrine facies complex is relatively poorly known, and its description is somewhat speculative. These basins contain significant coals and highly bioturbated shallow-water and fluvial sequences, suggesting more persistently humid conditions. The basins also are characterized by considerable thickness (>50 m) of microlaminated

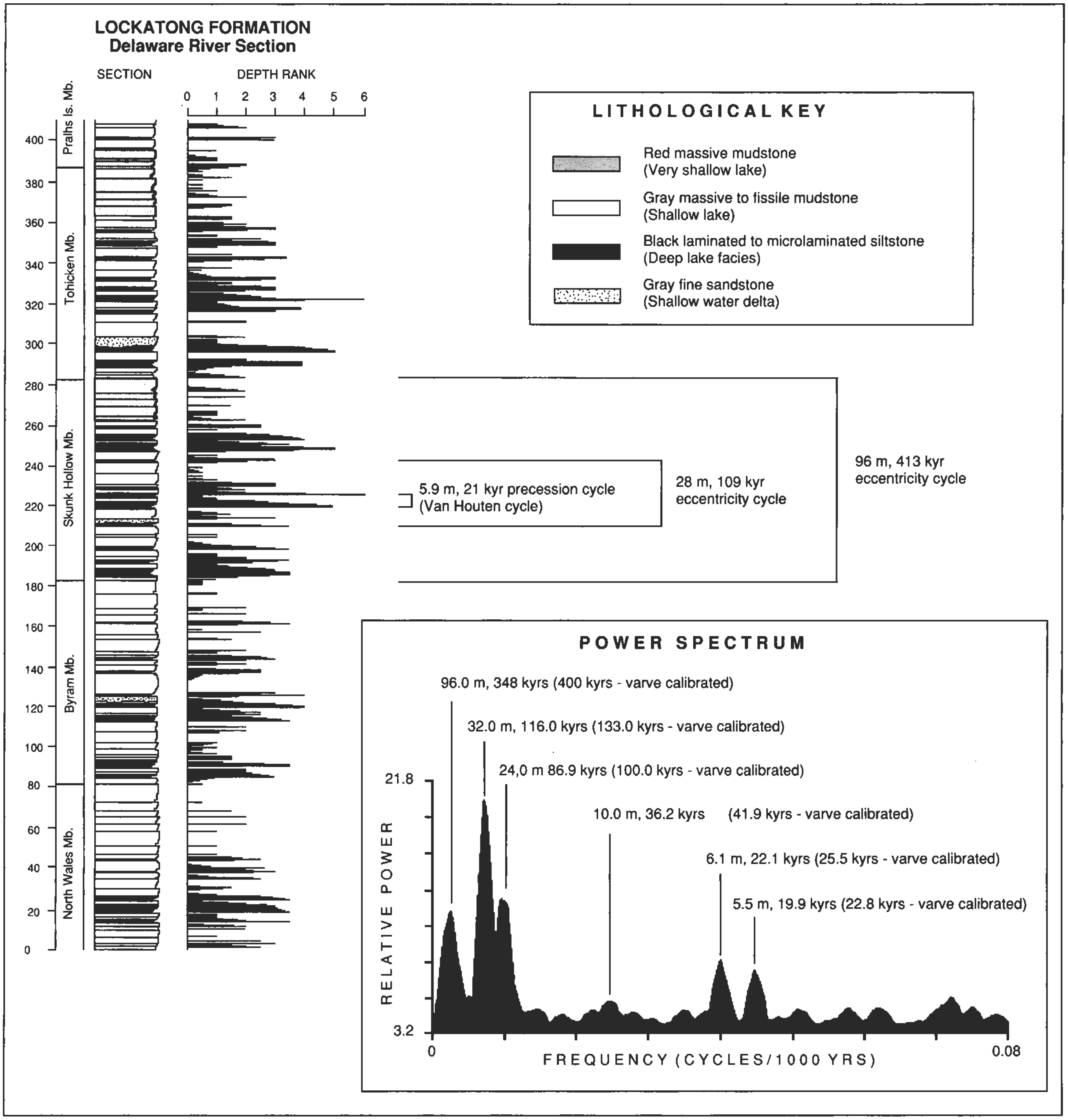

Figure 7. Section of Newark-type lacustrine facies complex in middle Lockatong Formation, Newark basin, and Fourier analysis of the Delaware river section, using the method described by Olsen (1986). Note that depth rank is a ranking of sedimentary fabrics in order of increasing inferred water depth.

siltstone interbedded with sandstone with no evidence of subaerial exposure (Figure 6). Relative to Newark-type basins, water inflow most often was greater than evaporation, and complete desiccation was rare. Consequently, the lake may have remained deep long enough that, on average, high-relief sedimentary features could have been built. These should include large prograding deltas, fan deltas, submarine channels, and turbidite fans. During the phase of the basin's history when deep lakes were possible because of the sedimentation-subsidence deficit, abrupt lateral changes in grain size of contemporaneous strata should be present, and large amounts of sand could be deposited virtually anywhere in the basin. When lake levels were low during longer-term climate cycles, such as the driest phases of 400-k.y. eccentricity cycles or longer cycles, high-relief features could be deeply eroded to produce large-scale unconformities and perhaps subaerial and subaqueous canyons. Large-scale depositional sequences bounded by sequence boundaries should characterize a major part of the basin fill. The ratio of organic-rich to organic-poor units would be high at least locally. Lakes Tanganyika and Malawi (not the specific structure) of the east African rift system appear to be reasonable modern analogs (Cohen, 1989) of the deep-lake phases of the Richmond-type lacustrine facies complex.

The Deep River basin of North Carolina and the Farmville and associated basins in Virginia appear to be of the Richmond type, except that microlaminated strata apparently are absent, suggesting that although desiccation was rare, the lakes never became as deep as in the Richmond or Taylorsville basins, perhaps because of lower outlet elevations (Gore, 1989; Olsen et al., 1989).

Fundy-type lacustrine facies complexes are characterized by a cyclicity consisting mostly of what are termed sand-patch cycles (Figures 5, 6) (Smoot and Olsen, 1985, 1988). These represent alternations between shallow perennial lakes and playas with well developed efflorescent salt crusts, perhaps representing the 100-k.y. eccentricity cycle (Olsen et al., 1989). These cycles are very thin (~1.5 m where exposed) compared with lake-level cycles in the more southern basins. Associated deposits in the Fundy basin include abundant gypsum nodules, salt-collapse structures (Olsen et al., 1989), and eolian dunes (Hubert and Mertz, 1984). Water inflow rarely matched evaporation, and deep-lake deposits are exceedingly uncommon. Consequently, as in Newark-type sequences, depositional relief within the basin would be very low, and lateral continuity of units would be extensive.. Sand should be uncommon in the basin center except for that of eolian origin in the sand-patch fabric and wave-reworked material from sand-patch cycles and eolian dunes. Because of the extreme rarity of deep lakes, virtually no organic carbon-rich intervals should be present. Saline Valley, California (Smoot and Castens-Seidel, 1982; Smoot and Olsen, 1988) seems a reasonable modern analog for the Fundy-type lacustrine facies complex.

The "wettest" looking basins with Richmond-type facies complexes are found in the southern Newark Supergroup, whereas the "driest" looking basins with Fundy-type facies complexes occur in the northernmost well-exposed basin (Figure 1). This apparent gradient could reflect a regional climatic gradient, altitudinal differences, or orographic effects. The fact that a Fundy-type facies complex occurs in the Argana basin of Morocco (Smoot and Olsen, 1988), which was at the same paleolatitude as the Newark basin, suggests that the apparent gradient has at least a strong altitudinal or orographic component, as suggested by Manspeizer (1982). It is critical to observe that climatic regime probably is more important to the style of lacustrine deposition in Newark basins than is tectonic environment, once the tectonic environment permitted a lake to develop.

The Newark Supergroup was located between latitudes -3°S and 8°N during the early Mesozoic, and qualitative as well as numerical models for this period suggest a strong monsoonal climate for the region (Robinson, 1973; Manspeizer, 1982; Kutzbach and Gallimore, 1989; Chandler, in preparation). The supercontinent of Pangea would produce supermonsoons perhaps accounting for the rather extreme expression of cyclicity (Figure 6) in Newark-type facies complexes. Whereas maximum lake depths were controlled by subsidence-sedimentation balance, their realized depths were controlled by climate.

The growth of an extensional basin through time also has a major direct effect on lake depths (Figure 4) (Schlische and Olsen, 1990). As described above, a given volume of water supplied by precipitation and balanced by evaporation might fill a deep basin when its area is small, but would be incapable of filling the basin as it widened. That is why I expect lacustrine extensional basins to show a slow decrease in apparent lake depth (both for humid and arid phases of climate cycles) after some maximum is reached early in the basin's history, even though the elevational difference between the outlet position and the sediment surface still might be increasing. Evidence for the continued presence of a high outlet are the rare deep-lake episodes in younger Triassic (Carnian) sections of the Newark Supergroup (Figure 4). These represent rare "superwet" events, which supplied much larger volumes of water than during "normal wet" phases of climate cycles. These events could produce a deep lake only because of the presence of a high outlet.

High-frequency lake-level oscillations are not at all unique to the Newark Supergroup or the early Mesozoic. Perhaps the most striking example is the Devonian Caithness Flagstones of the Orcadian basin in Scotland (Figure 8), which has cycles similar to the Van Houten cycles of Newark-type complexes (Donovan et al., 1974; Donovan, 1980; Janaway and Parnell, 1989). It has long been known that large lake basins of the Basin and Range province of the western United States have experienced large-scale lake-level cycles controlled by cyclical climate (Gilbert, 1890), and the great lakes of east Africa apparently have experienced even larger lake-level oscillations (Johnson et al., 1987; Scholz and Rosendahl, 1988), although not at such a high frequency.

LAKE DEPTH CONTROL OF MATERIAL DISTRIBUTION

In large tropical lakes, depth is the main control on material distribution. This is because the main sources of energy for vertical and horizontal material transport are turbulence and currents driven by the wind, the work of which is transmitted through the surface of the lake. Depth of wave base, one measure

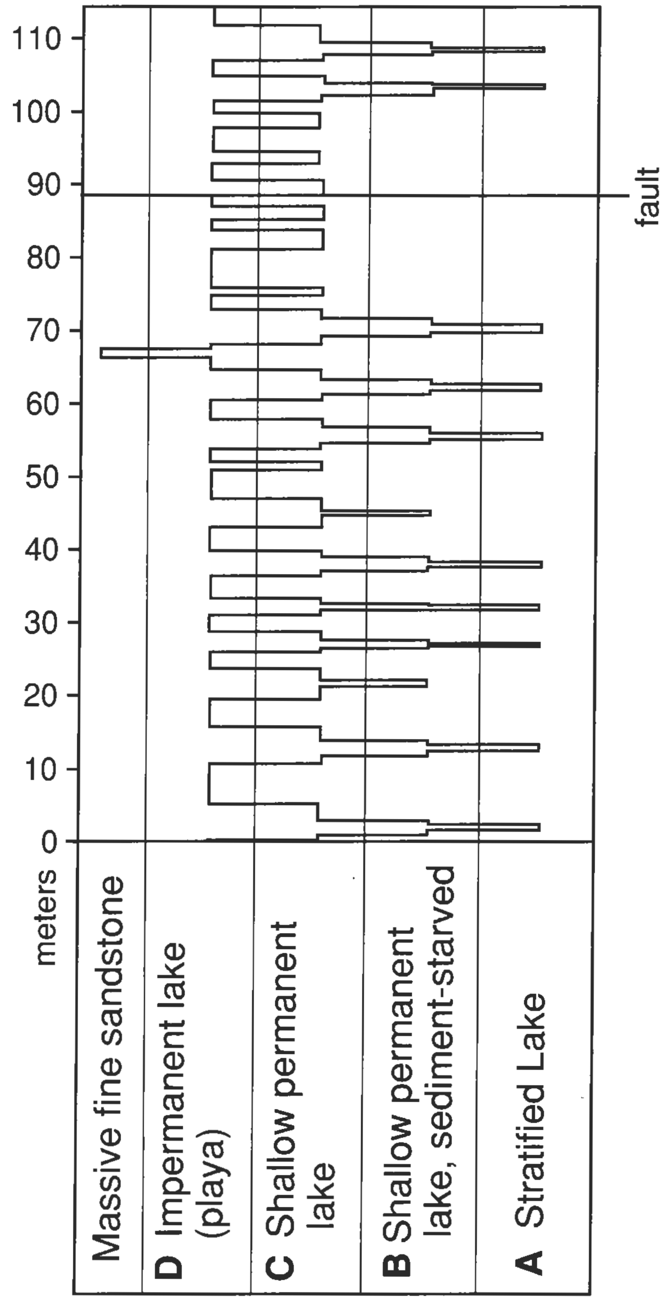

Figure 8. Sedimentary cycles in Caithness Flagstones of the Orcadian basin, Scotland (adapted from Donovan, 1980). Lacustrine facies types ranked in order of increasing inferred water depth in a manner analogous to Olsen (1986).

of this work, is a function of the distance over which the lake is exposed to wind (fetch) and the speed and duration of the wind itself. All other things equal, a lake covering a larger surface area has a deeper wave base than a lake covering a smaller area. For two lakes of equal area, the deeper lake will have a smaller proportion of its water column affected by wave mixing than the shallower one.

Manspeizer and Olsen (1981) and Olsen (1984a) have developed a relationship among fetch, wind speed, and wave base (Figure 9) using the semiempirical equations of Bretscheider (1952) and Smith and Sinclair (1972). Depth of wave base calculated for wind speeds of 10–40 m/sec correlates well ($r^2 = 0.95$ for a 30-m/sec wind) with depth of the chemocline in nonsaline, tropical stratified lakes (Figures 9 and 10). This is because the chemocline is maintained by an active, turbulent, wind-mixed surface layer that is dependent on area in a way similar to wave base. Observations of the chemocline in stratified lakes such as Tanganyika and Malawi show it deepening during windy periods and shallowing during calm times (Beadle, 1974). The reason these lakes become chemically stratified is that, below the turbulent mixed layer, oxygen is transported from the surface too slowly to allow aerobic breakdown of all organic matter produced within and washed into the lake. Thus, the deeper areas of the lake become anaerobic. Stratification in turbulence exists because the lake is deep compared to its possible fetch. That chemical stratification follows the boundaries of turbulent stratification is a consequence mostly of high organic productivity.

Lakes of similar dimensions as tropical stratified lakes but with low organic production rates do not become chemically stratified, even though turbulent stratification is present. Lake Baikal has nearly the same dimensions as Lake Tanganyika and definitely exhibits turbulent stratification (Carmack et al., 1989; Figure 10). However, primary production values are relatively low, 25–100 g C/m^2/yr (Likens, 1975; Weiss et al., 1989), compared with Lake Tanganyika's 328 g C/m^2/yr (Hecky and Fee, 1981). Hence, although turbulent stratification exists in Baikal, primary productivity is insufficient to develop perennial anoxia in the water mass below the turbulent layer. The same relationship between possible fetch and wave base suggests that lakes shallower than their predicted wave bases should not become perennially stratified. This seems to be borne out by observation (Figure 10). It must be noted, however, that this is mostly an empirical relationship, not a hydrodynamic one, and the exact relationship among chemocline position, wind, and lake dimension has yet to determined. Gorham and Boyce (1986) reported a similar empirical relationship between thermocline depth and fetch in temperate lakes, although thermocline depth is generally much shallower.

Nonetheless, the empirical relationships in Figures 9 and 10 permit some understanding of how deep some Newark Supergroup lakes were during their highstands. For example, individual microlaminated shales within single Van Houten cycles of the Lockatong Formation have been traced about 180 km across the Newark basin (Olsen, 1984a, 1988). Within these strata are submillimeter-thick laminae, traceable over large areas and often containing articulated fish and reptile fossils. Pinch-and-swell laminae are rare within the microlaminated inter-

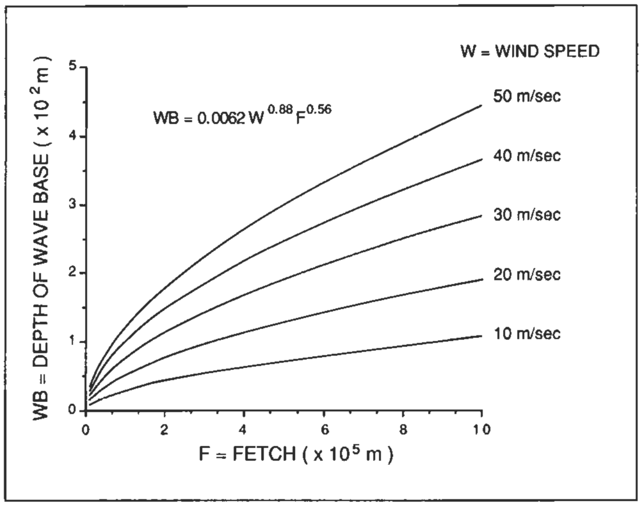

Figure 9. Calculated relationships between maximum potential fetch of a lake and predicted wave base for winds of various speeds, based on equations in Olsen (1984a) and Manspeizer and Olsen (1981).

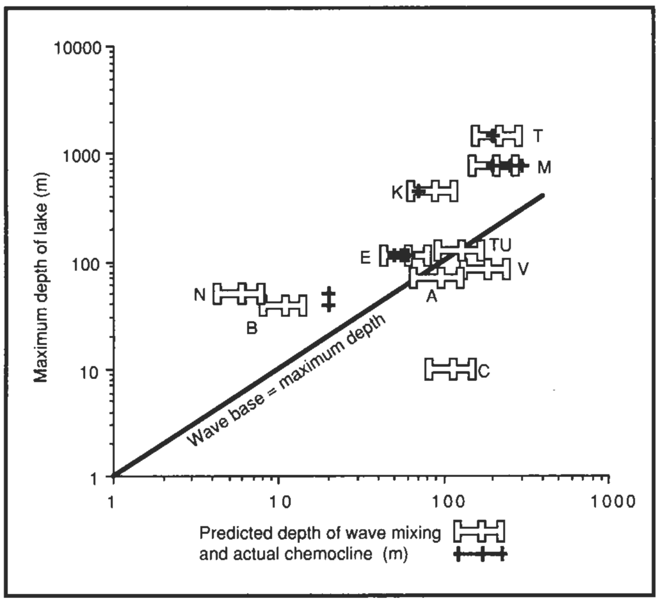

Figure 10. Relationship between predicted depth of wave base and actual depth of chemocline for several east African lakes. Abbreviations: A, Lake Albert; B, Lake Bunyuni; C, Lake Chad; E, Lake Edward; K, Lake Kivu; M, Lake Malawi; N, Lake Nhugute; T, Lake Tanganyika; TU, Lake Turkana; V, Lake Victoria. Note that for lakes in which maximum depths are less than predicted depths of wave mixing, no chemocline exists, and oxygenated waters reach the lake bottoms. Note also that Lake Biakal would plot almost coincidentally with Lake Tanganyika (T) in predicted depth of wave mixing, lake depth, and depth to the base of the measured turbulent layer; it has no chemocline, and oxygen reaches the bottom. Calculated depth of wave mixing is based on relationships in Figure 9 and data in Beadle (1974).

vals. If we reasonably assume that these microlaminated strata were not exposed to wave base during their deposition, then the longest dimension of the microlaminated unit can be used to calculate a minimum lake depth using the unit's length as the maximum potential fetch (Manspeizer and Olsen, 1981; Olsen, 1984a). For the Lockatong Formation this method yields depths of about 70, 100, and 130 m for wind speeds of 20, 30, and 40 m/sec, respectively (Olsen 1984a). The absence of bioturbation in these layers together with the preservation of whole fish and reptiles suggest an anoxic bottom. Therefore, these estimates represent minimum depths to the chemocline, and the lakes could have been much deeper.

ECOSYSTEM PRODUCTION, CONSUMPTION, AND EFFICIENCY

The main sources of energy for lacustrine ecosystems are primary production and inflow of allochthonous organic material. The balance between production and consumption of this organic material is mediated by the relationship between the lake's upper mixed layer and its depth.

The amount of organic material that accumulates in sediment is a function of ecosystem efficiency (ratio of ecosystem respiration to production $\times$ 100), which is highest in shallow water and lowest in deep water. Most aquatic ecosystems are extraordinarily efficient (approaching 100%), and even those that do produce organic-rich sediment only lose a small fraction to the sediments. The Black Sea has an ecosystem efficiency of about 96%, losing only about 4% of primary production to the sediment (Degens and Ross, 1974).

In the turbulent layer of a lake the residence time of an organic particle in the water column is relatively long, and the diffusion rate of oxygen is high. Numerous detritovores further mill down large particles, and bioturbators recycle sedimented material. Below the turbulent layer, in tropical lakes, residence time is relatively short, and the diffusion rate of oxygen is much less. Bacterial activity tends to consume available oxygen at a rate greater than can be supplied, and the water column becomes anoxic. Although researchers still debate whether aerobic or anaerobic organisms are more efficient consumers, the key to the slower consumption rates in the anaerobic zone is probably the much reduced range of organisms there and shorter residence time of organic particles in the water column. Consequently, the anoxic water mass (hypolimnion) is less efficient at consuming organic matter than the upper mixed layer.

The depths of lakes thus have a powerful control on the efficiency of their ecosystems. In the Newark Supergroup black microlaminated units were produced only in the deepest, probably perennially chemically stratified lakes, with depressed ecosystem efficiencies and little or no bioturbation. In contrast, shallow lakes of high ecosystem efficiency produced mostly red or gray massive mudstone with little or no preserved organic material, even though they probably had as high or higher primary productivity. The fluctuations in organic-carbon content characterizing Van Houten cycles reflect changing ecosystem efficiency much more than changing productivity. The same control probably is responsible for the remarkably different sedimentary carbon contents in Lakes Turkana and Tanganyika, both of which are fairly productive (Hecky and Fee, 1981; Cohen, 1984). However, Turkana has low carbon values associated with a shallow lake (maximum depth 125 m), while Tanganyika has high carbon values and greater depth (1400 m).

HISTORICAL TRENDS

Both production and consumption rates depend not only on proximal causes, such as relative depth of the water body and nutrients levels, but also on ultimate causes such as long-term evolution of new consumer groups with new innovations.

The effects of long-term historical trends are most apparent in the bioturbation of lacustrine sediments, just as in marine sediments (Thayer, 1979). Freshwater systems have very low diversities of bioturbators compared to marine systems (Lopez, 1988), and many of the groups responsible for lacustrine bioturbation appear to be of relatively recent origin. Apparently through the Phanerozoic there is a trend of increasing bioturbation of sediments deposited under low-oxygen conditions following the evolution of bioturbators tolerant of low-oxygen environments (Figure 11).

In modern lakes the important macrobioturbators in low-oxygen conditions are tubificid worms, ostracodes, chironomid and chaoborid fly larvae, and sphaerid and unionid clams (Lopez, 1988) (Figure 11). However, no definite tubificid worms nor any definitive oligochaetes are known in the fossil record (Conway et al., 1982), except for some possible Carboniferous tubificid fossils (Gray, 1988). Modern darwinulid ostracodes, which can tolerate brief periods of low or no oxygen, are known from putatively freshwater deposits as old as Ordovician (Gray, 1988). The oldest known true flies are Triassic in age (Olsen et al., 1978; Wootton, 1988), and although they belong to the larger group containing chaoborid and chironomid flies (Nematocerata), chironomids are not known before the Jurassic (Kalugina, 1980; Gray, 1988), and chaoborids are not known before the Cretaceous (Gray, 1988). Clams of the order Unionoida are known from the Devonian (Gray, 1988), often from organic-rich rocks. However, members of the heterodont family Sphaeridae, including the important anoxia-resistant *Pisidium* (Gray, 1988), are not known until Late Jurassic. Of course, clams leave obvious fossils, and their presence usually is easily recognized.

Based on first appearances of groups, entire suites of critical modern bioturbators are absent from progressively more ancient lakes. We can therefore expect that a wider range of ancient, low-oxygen lacustrine environments should have excluded more bioturbators than at present. This means that many ancient lakes with only seasonally anoxic or low-oxygen bottom waters could have accumulated sediment devoid of bioturbation. In addition, because bioturbators under low oxygen levels are ventilators of the sediment and consumers of organic material, their absence would therefore reduce the lake's ecosystem efficiency and encourage more complete bottom anoxia under lower levels of primary production than obtained today. A higher proportion of older than younger lacustrine strata should therefore be microlaminated.

An extreme example of this trend can be seen by comparing a hypothetical early Proterozoic lake with a modern one. The Proterozoic lake produced microlaminated sediment in all situations of slow, fine-grained, suspension-dominated deposition below wave base, regardless of bottom-water oxygen levels or levels of primary production. In contrast, a modern lake with moderately high productivity has bioturbators in all environments except those perennially devoid of oxygen. Lakes of intermediate age should be bioturbated to intermediate extents. Therefore, the absence of macroscopic bioturbation in the deepest water Newark Supergroup lakes cannot be assumed necessarily to reflect perennial anoxic bottom waters. Simple analogy to modern lakes is inappropriate because the biological context has changed.

Newark Supergroup lakes probably experienced some degree of bioturbation in low-oxygen environments by ostracodes, possibly tubificid worms, and perhaps sphaerid and unionid clams. However, on the whole, a considerably wider range of oxygenation conditions probably resulted in the production of microlaminated sediment because of the absence of key bioturbators, such as chironomids. In addition, the frequency with which the lakes became chemically stratified probably was somewhat greater than we would expect from our knowledge of modern lakes.

These processes and relationships are only some of the factors important to lake system ontogeny and lacustrine ecosystem evolution. Not discussed here is *in situ* evolution of lacustrine organisms that occurs during the life cycle of an individual lake, for example, during one 21-k.y. climate cycle (McCune et al., 1984). Important successional processes occur on even faster time scales (Lopez, 1988).

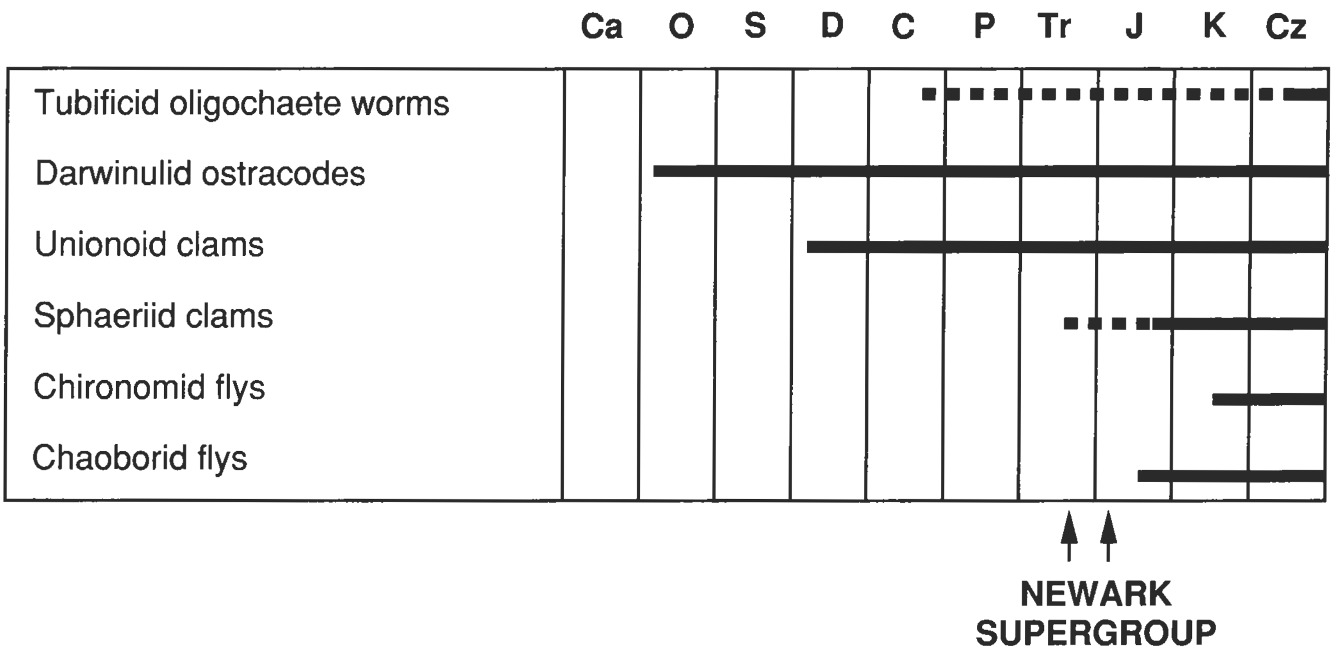

Figure 11. Times of appearances of major mud bioturbators in modern lakes. Based on data from Gray (1988) and Wootton (1988).

CONCLUSIONS

Tectonism produces a subsiding basin and controls its overall geometry, but basin filling by sediment interactively alters the geometry of the depositional surface in predictable ways. The distinctive tripartite stratigraphic pattern (fluvial, deep lake, shallow lake or fluvial) seen in extensional lacustrine basins may be due to basin filling during a long-lived pulse of extension.

Lake systems owe as much to climatic milieu as to tectonic and basin-filling processes, however. The balance between water inflow and outflow (principally by evaporation) is the critical factor governing the depths and duration of individual lakes (as opposed to the lake basin). Relatively high-frequency climatic cycles induce lake-level cycles that follow the 21-, 41-, 100-, and 400-k.y. Milankovitch cycles caused by variations in the Earth's orbit. The magnitude of these lake-level changes is governed by position within the climate system and by orography. Thus, even in a region as limited as eastern North America, one finds major differences among basins.

The frequency and magnitude of lake-level changes have major effects on the types of lacustrine sedimentary environments. Within the Newark Supergroup three types of lacustrine facies complexes are recognized (in order of increasing severity and frequency of low lake levels)—Richmond, Newark, and Fundy types.

Lake level controls ecosystem efficiency, which in turn is responsible for the loss of organic carbon-rich material to lake sediments. All other things equal, lakes that are deep compared to their areas tend to be more inefficient than others. Hence, lake-level cycles are reflected in sedimentary cycles wherein shallow-water strata are organic carbon poor, and deep-lake strata are organic carbon rich. Ultimately, control of lake metabolism is a function of the evolution of diverse organisms capable of surviving the range of lacustrine environments. The long-term trend in the degree of bioturbation of lacustrine sediments through the Phanerozoic probably reflects the proliferation of organisms capable of surviving low-oxygen environments. This long-term trend must be taken into account in paleoenvironmental interpretations of ancient lacustrine systems because it affects not only the range of sediments that escape bioturbation but also the frequency with which stratified lakes can develop.

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