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High-resolution early Mesozoic Pangean climatic transect in lacustrine environments

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with 8 figures

Abstract: Analysis of 6700 m of core from the Newark rift basin in New Jersey, USA provides a high-resolution astronomically calibrated magnetic polarity time scale for the Late Triassic and Early Jurassic spanning about 33 million years. This time scale, and its application elsewhere, allows a significant simplification of the pattern of climate-sensitive facies in the early Mesozoic basins of the central and north Atlantic margins. Coals and deep-water lacustrine deposits were produced at the paleoequator (Richmond-type sequences), while strikingly cyclical lacustrine and playa deposits were produced 10° to the north and south (Newark-type lacustrine sequences). At 10–30 °N, eolian dunes, playas sediments and evaporites were deposited (Fundy-type sequences). Farther north, shallow-water lacustrine red beds were deposited (Fleming Fjord-type sequences), while yet farther north (~40°), perennial-lake black mudstones and coals again dominated in the humid temperate zone (Kap Stewart-type sequences). Central Pangea drifted north about 10° during the Late Triassic, and the vertical sequence of climate-sensitive facies in individual basins changed as the basins passed through different climate zones. This simple zonal climate pattern explains most first-order changes in overall lacustrine sequences seen in the rift zone. Lake-level cycles of Milankovitch origin change in a predicable way with the latitudinal shifts in climate and lacustrine style. Roughly 10 ky precessional cycles dominate within a few degrees of the equator, while ~20 ky precessional cycles are dominant northward to about 30 °N where ~40 ky obliquity cycles become evident in lake-level records.

Introduction

Stratigraphic correlation provides the framework for understanding ancient Earth systems. If stratigraphic resolution is poor, so will be the understanding of the system. Advances in paleoclimatology, especially aspects related to orbital forcing, have shown the permeating and persistent nature of relatively high-frequency (~10– ~20 ky) climate cycles throughout geological time. Given the poor resolution thought to be typical of interbasinal correlations in the early Mesozoic, outdated paleogeographic control, and high frequency climate change, it is hardly surprising that the lacustrine and related strata, preserved in numerous rift basins and rift-related basins from Svalbard to the Gulf of Mexico, have been depicted as

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displaying a baffling array of climate-sensitive lithologies. The seemingly conflicting associations of facies have prompted several ad hoc explanations invoking non-zonal climatic processes such as monsoons, the effects of topography, and global climate change (e.g. Manspeizer 1982, Parrish 1992).

Cyclostratigraphic and paleomagnetic analyses of 6700 m of core from the Newark basin collected by the Newark Basin Coring Project (NBCP – Olsen et al. 1996a) provide a high-resolution, astronomically calibrated, magnetic polarity time scale for the Late Triassic and Early Jurassic spanning about 32 million years (Kent et al. 1995, Olsen and Kent 1999). This time scale allows global correlations at intra-Neogene-level of resolution. In this paper we summarize our attempts to extend high-resolution correlations along a N-S transect from about 30 °N paleolatitude to the paleoequator along the axis of what would later become the Central and North Atlantic Oceans (Fig. 1). We use these correlations to place the basin sequences into a simple climatic scheme.

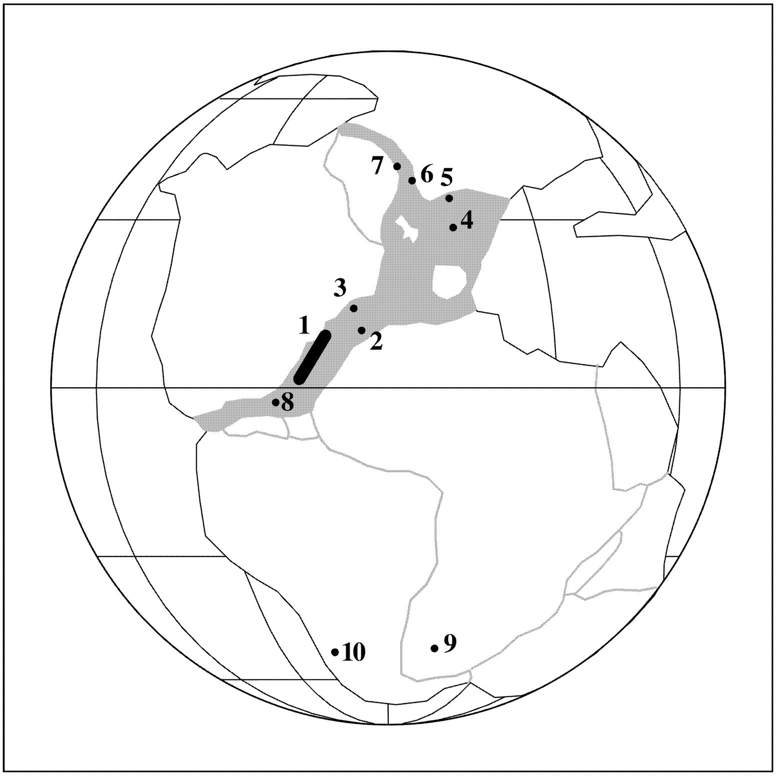


Fig. 1. Triassic-Early Jurassic zone of rifting (gray) in north-central Pangea. Reconstruction is modified from Olsen et al. 1996a and is for 210 my (Norian). Basins discussed in the text are: 1. Southern Newark Supergroup basins; 2. Argana basin; 3. Fundy basin; 4. Germanic basin; 5. Danish-Polish basin; 6. Haltenbanken; 7. Jameson Land basin; 8. South Georgia basin; 9. Karoo basin; 10. Ischigualasto basin.

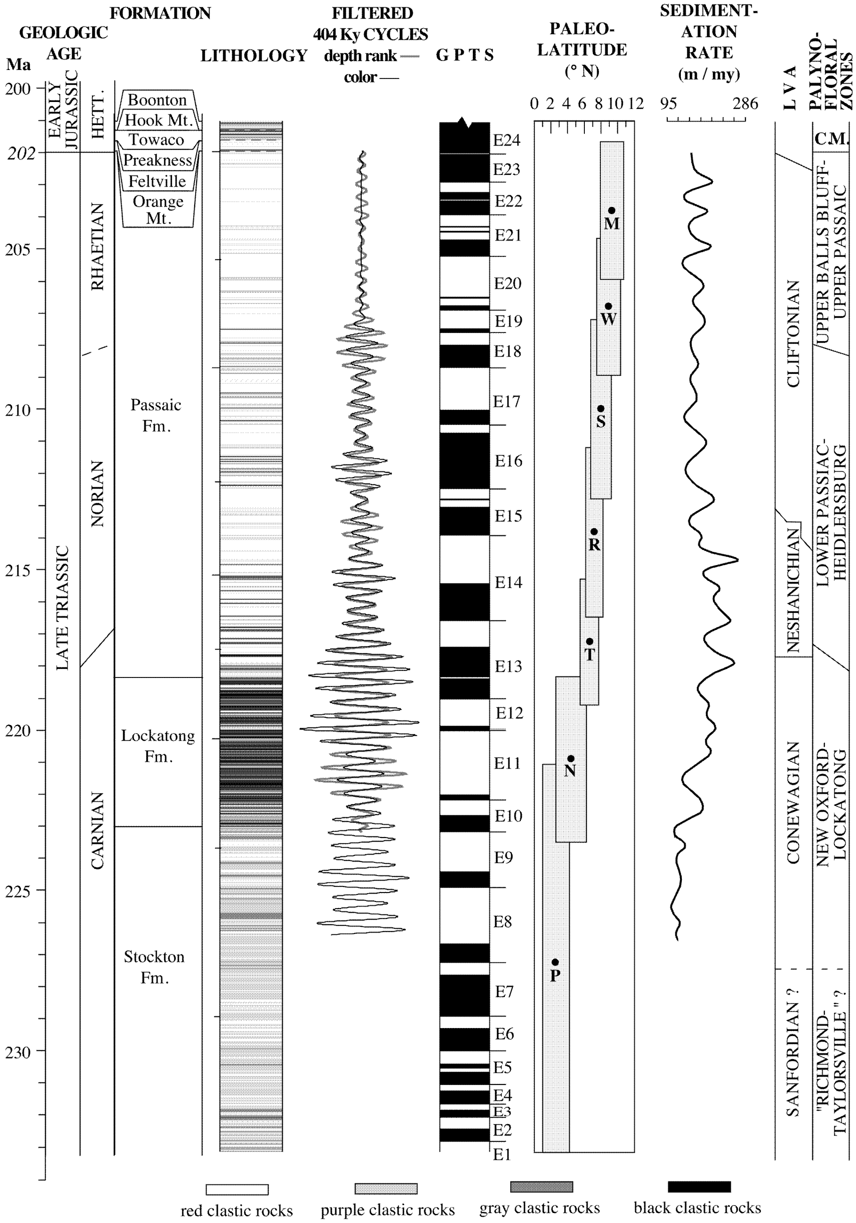
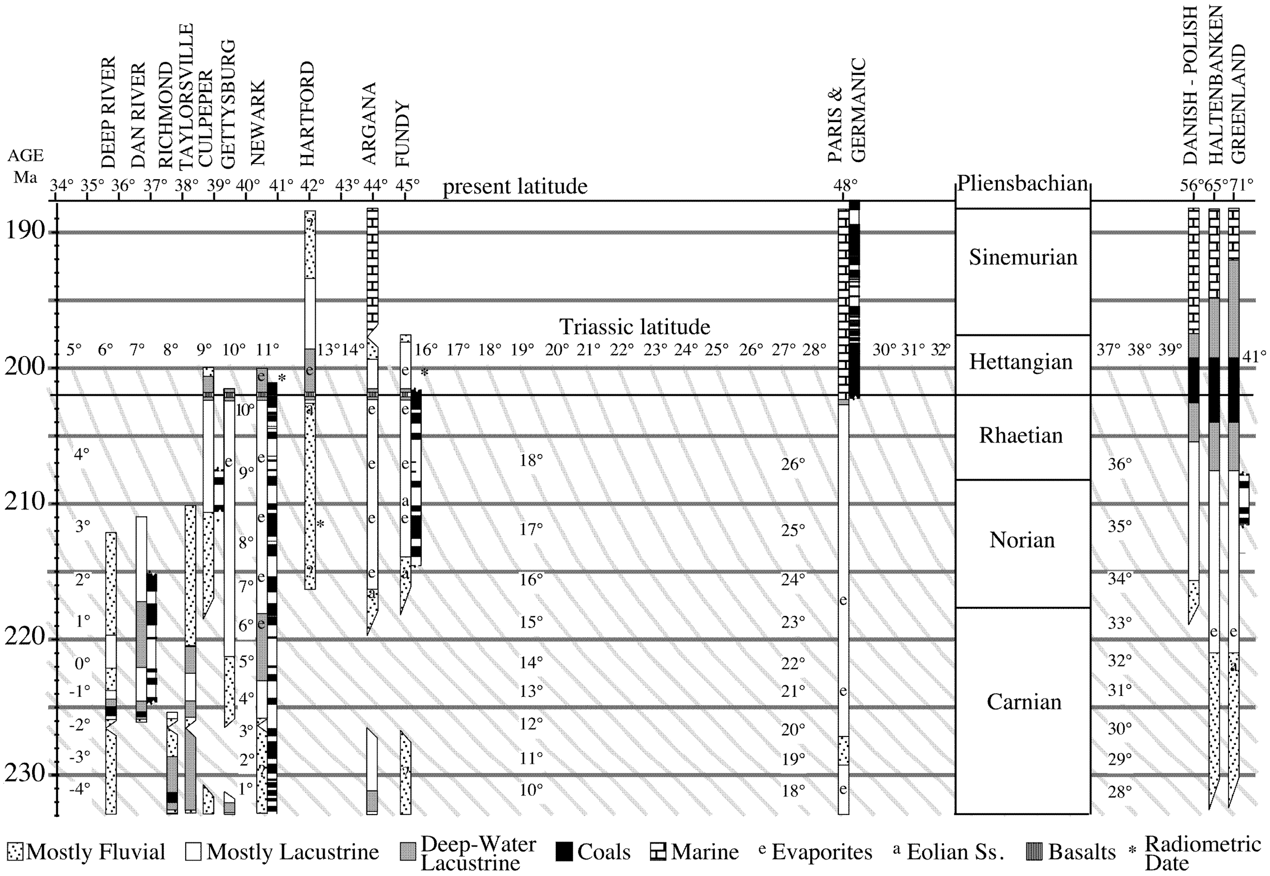


Fig. 2. Newark basin time scale, modified from Olsen and Kent (1999). Asterisks in lithology column indicate basalt flow horizons (dashed lines in lithology column) shown here represent zero duration (e.g. Olsen et al. 1996b). Magnetic polarity and paleolatitudes from Kent et al. (1995). Italicized date (*202*) under GEOLOGIC AGE is the absolute age tie point based on radiometric dates of lave flows.


AGE
Ma
DEEP RIVER
DAN RIVER
RICHMOND
TAYLORSVILLE
CULPEPER
GETTYSBURG
NEWARK
HARTFORD
ARGANA
FUNDY
PARIS &
GERMANIC
DANISH - POLISH
HALTENBANKEN
GREENLAND
34° 35° 36° 37° 38° 39° 40° 41° 42° 43° 44° 45°
present latitude
48°
56° 65° 71°
Pliensbachian
Sinemurian
Hettangian
Rhaetian
Norian
Carnian
Triassic latitude
5° 6° 7° 8° 9° 10° 11° 13° 14° 16° 17° 18° 19° 20° 21° 22° 23° 24° 25° 26° 27° 28° 30° 31° 32° 37° 38° 39° 41°
190
200
210
220
230
4° 3° 2° 1° 0° -1° -2° -3° -4°
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Newark basin time scale

Based on the NBCP cores, the Newark basin time scale spans about 33 million years, of which about 25 million years are calibrated by lake level sequences under Milankovitch climate cycle control (Fig. 2, Olsen et al. 1996a, Olsen and Kent 1996, Olsen 1997). We delineate roughly 58 major magnetic polarity intervals with a mean duration of 0.5 my (Kent et al. 1995, Kent and Olsen, this volume 1999). A roughly 20 my-level of resolution is permitted by the detailed cyclostratigraphy in the younger 22 million years of the time scale, while the older part is calibrated to only the 400 ky-level. Radiometric dates from feeders to the interbedded lava flows in the most recent million years of the record place the entire Newark basin time scale within absolute years with an estimated error of about ±1 my. Within the Newark basin this time scale has been extensively tested (Kent et al. 1995, Olsen et al. 1996a, Olsen and Kent 1996, Kent and Olsen 1999a, 1999b) by comparison of magnetic polarity stratigraphy and cyclostratigraphy over distances in excess of 180 km. We have also tested the constancy of the paleolatitudinal estimates and polarity stratigraphy by detailed comparisons with the Dan River basin section some 500 km away (Kent and Olsen 1997). The close correspondence of both the apparent pole positions and polarity stratigraphy of these two basins makes it very unlikely that tectonic rotations have biased the Newark basin paleomagnetic record.

Extension of the Newark basin time scale to other basins

Thus far we have been able to produce at least preliminary magnetic polarity stratigraphies for significant portions of several major basins over a roughly 30° swath of paleolatitudes (Fig. 3). From south to north, these basins include: the Dan River basin of Virginia and North Carolina (Kent and Olsen 1997), the Taylorsville basin of Virginia (LeTourneau et al. 1998), the Culpeper basin of Virginia, the Argana basin of Morocco, the Fundy basin of Maritime Canada, and the Jameson Land basin of East Greenland (Kent and Clemmensen 1996, Clemmensen et al. 1998). Along with biostratigraphy, particularly that based on palynomorphs and tetrapods (Cornet 1993, Fowell et al. 1994), these correlations allow rigorous comparisons of climate-sensitive lithologies along 30° of paleolatitude (Fig. 3). The paleomagnetic data are preliminary and the subject of ongoing projects (with

Fig. 3. Matrix showing relationship between main climate-sensitive lithologies, age, geography and paleomagnetic polarity stratigraphy (black and white bars) for the basins discussed in text. Curved gray lines are lines of equal paleolatitude based on the Newark basin section (Newark basin polarity scale from Kent et al 1995. Other basin sections are based on the following: Culpeper and Fundy are based on our more recent work in progress; Dan River (Kent and Olsen 1997); Paris basin (Yang et al. 1996); Jameson Land (Kent and Clemmensen 1996).

the exception of the Newark and Dan River basins), and therefore the paleomagnetic stratigraphies are given in outline form only. We have also included other basin sections in Figure 3 that we believe are correlated finely enough by biostratigraphy to allow at least first-order comparisons.

General climatic pattern

With the Newark basin time scale and paleolatitudinal data in hand, the overall pattern of climate-sensitive facies in the Triassic and Early Jurassic is greatly simplified (Olsen 1997). Most clear is a more or less symmetrical arrangement of facies around the paleoequator during Carnian time. Coals and deep-water lacustrine deposits were produced in the Deep River, Dan River, Richmond, and Taylorsville basins (summarized in Olsen 1977) around the paleoequator, while strikingly cyclical perennial lacustrine and playa deposits and bioturbated red beds were produced 10° to the north and south (Kent and Olsen 1997). Broadly contemporaneous deposits at 30 °N paleolatitude in Greenland (Clemmensen 1980, Clemmensen et al. 1998) and the Haltenbanken area of offshore Norway (Hollander 1984, Hagevang and Ronnevivk 1986, Withjack et al. 1990) are comprised of red mudstones, eolian sand dunes, and evaporite beds, while further north in the Barents Sea, deltaic coals and black mudstone again dominate (Van Veen et al. 1992). This conforms to a simple zonal pattern, with a narrow equatorial humid zone and an arid belt mostly south of 30°, passing northward into hot house humid temperate climates. Basins in the Triassic southern hemisphere show the same pattern, although their stratigraphy is much less tightly calibrated in time. For example, Carnian age red beds are present in the South Georgia basin (Moy and Traverse 1986), while Carnian age gray mudstones (Argentina) and coals (Karoo basin, southern Africa) are present farther south. Although non-zonal elements such as orography and an enhanced monsoon may have been important elements of the Earth's climate system during the Carnian, such are not required by the observations.

As Pangea drifted northward, the vertical sequence of climate-sensitive facies within individual basins changed as the basins passed from one climate zone to another. Thus, in each basin within the Newark Supergroup of North America (North Carolina to Nova Scotia) and in Morocco, the transition from Carnian through Norian age strata is characterized by apparent drying with shallow water cyclical lacustrine strata predominating in the southern basins, specifically the Newark, Gettysburg, Culpeper, Taylorsville, and Dan River basins (Olsen 1977). Conversely, in northern and eastern Germany, England, Poland, Sweden, the Haltenbanken area and Greenland, the vertical Late Triassic sequence within individual basins is from red beds and evaporites upward into black lacustrine, paludal, and paralic shales (Norling et al. 1993, Bilan W 1991, Hollander 1984, Hagevang and Ronnevivk 1986, Withjack et al. 1990, Clemmensen 1980). This vertical pattern within basins fits the same basic geographic pattern seen in Carnian data except that the pattern shifts south in present geographic coordinates and, hence, is consistent with a northward drift of central Pangea.

A similar pattern, with lower level of resolution, is seen in individual basins in the Triassic southern hemisphere. Examples include younger Triassic and Early Jurassic strata in the Ischigualasto and Karroo basins of Argentina and southern Africa, respectively. In both basins the sections become dominated by red beds and then eolian dune sands upward, again consistent with a northward drift of that part of Pangea.

However, within this broad pattern, there are some apparent anomalies. In particular, the Schilfsandstein of the Germanic basin appears to have been deposited in notably more humid conditions than stratigraphically surrounding deposits (Simms and Ruffell 1990). No physical arid indicators, such as evaporites or eolianites, are known and occasional thin coal beds and abundant plant fragments are present. Visscher et al. (1994) attribute this apparent anomalous humid interval to ground water conditions in an essentially arid overall environment. However, we note that strata correlated with the Schilfsandstein on the basis of vertebrates and palynomorphs in eastern North America also appear to have been deposited under slightly more humid conditions. However, the significance of this anomaly, along with the supposed Carnian “pluvial event” of Simms and Ruffell (1990), will be difficult to assess until more precise correlative techniques (e.g. magnetostratigraphy) are more broadly available for this part of the Late Triassic.

In the Newark Supergroup and in Morocco, there is an additional major, but short lived, departure from the pattern seen in the Carnian and Norian age beds. In strata of latest Rhaetian and earliest Jurassic age, more humid cyclical deposits appear more or less concurrently with an enormous extrusion of flood basalts. Because this apparent reversal in the paleoclimatic trend is not accompanied by a drift of Pangea to the south, it must reflect a true climate change. This kind of climate change might be expected from a spread of the ocean closer to the region, as occured in the Early Jurassic flooding of western Europe, perhaps generated by massive flood basalt eruptions (Olsen et al. 1997). A true climate change for this time interval may also be indicated by the stratigraphically abrupt transition into coal-bearing sequences in the Danish-Polish and East Greenland-Haltenbanken areas (e.g. Clemmensen et al. 1998) during a time of slow northward drift. However, because we lack cyclostratigraphic and magnetostratigraphic data in this geographic area through the Triassic-Jurassic transition, we do not know if this transition was broadly synchronous over the area or consistent with a very sharp geographic gradient between climatic zones.

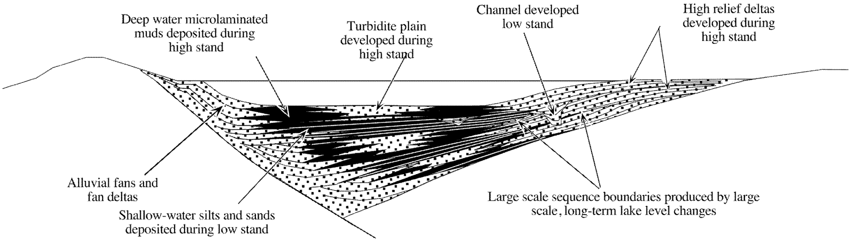
Lacustrine styles and orbital forcing

Within the 30° of latitude spanned by the sequences discussed above there are profound changes in both the overall stratigraphic architectural style and the component sedimentary cycles of lacustrine strata. Olsen (1990) described three styles of lacustrine sequences in Eastern North America which, from the equator northward, are termed the Richmond, Newark, and Fundy type lacustrine sequences (Fig. 4). Farther north, the Fleming Fjord and Kap Stewart style lacustrine sequences (Fig. 4) can be added.

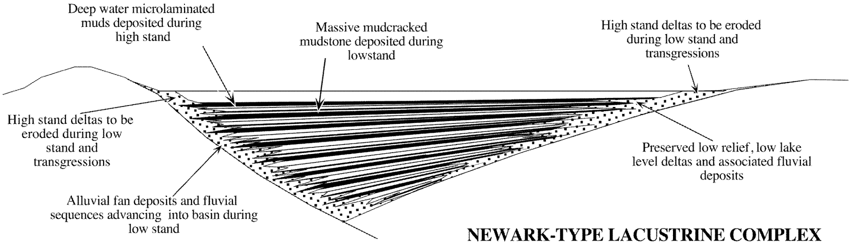
Richmond style lacustrine sequences are characterized by indicators of long term submergence and relatively muted climatic cycles (Figs. 4a, Fig. 6a). During relatively deeper water phases of the section, thick black shale sequences are interbedded with sandstones in the basin center, while much coarser strata interfinger along the basin margins. Black mudstones and carbonates are frequently microlaminated and contain a characteristic taphocoenesis of articulated fish with an absence of bioturbation. Based on industry drilling logs and seismic data Cornet and Olsen (1990) suggested that there appears to be significant relief on fluvial and deltaic structures within and adjacent to the black shale sequences. Cores and outcrops indicate the presence of abundant turbidites, sublacustrine channels, and fan deltas far into the basin. Shallower water phases of the basin sections have more prominent cyclicity, but the drier parts of the cycles tend to be sandy with intense bioturbation. Significant coal bearing intervals can be present in the shallower water intervals (e.g. the “productive coal measures”). Richmond style lacustrine sequences have been found in the Richmond, Taylorsville, Briery Creek, and Scottsburg basins of Virginia.

Newark-style lacustrine sequences are the most common type in eastern North America (Figs. 4b, 5) and have a very extensive descriptive literature (Smoot and Olsen 1994 and Olsen 1977), being characterized by very pronounced cyclicity caused by alternating intervals of submergence and desiccation at time scales of 20 ky. Basin center facies tend to be fine-grained with low-stand intervals dominated by red or gray mud-cracked massive mudstone and rooted mudstone. Deeper water intervals consist of black to red shales, with black shales frequently being microlaminated with the same basic taphoceoensis as in the Richmond-style sequences. Coarse clastic rocks are more restricted to the margins of the basin than in Richmond-type sequences. Deeper-water parts of the basin sequences can be mostly gray, but each sedimentary cycle has evidence of desiccation, even though the cycles may have a very prominent black shale. Shallower water phases of the basin sections tend to be mostly red clastics with less bioturbation than Richmond-style sequences. Coals are rarely present, but some are present in the more southern basins. Evaporites can be fairly abundant, although no pure bedded evaporites have been identified. The evaporite-bearing beds are almost always in the shallower-water parts of cycles, usually with dessication cracks and sometimes reptile tracks. The overall stratigraphic architecture tends to be characterized by virtually no evidence of significant topography. Newark-type sequences have been

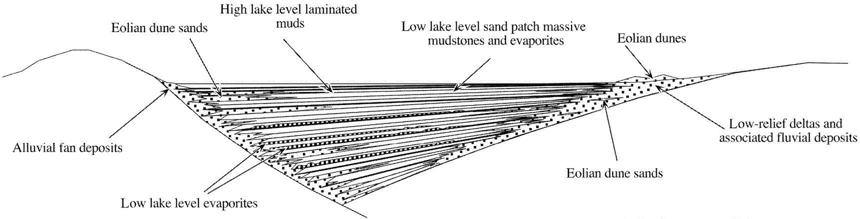
Fig. 4. Cartoons of the five types of lacustrine complexes in the Triassic-Jurassic rifting zone. The upper three are modified from Olsen (1990); the Fleming Fjord-type complex is based on Clemmensen (1980) and Seegis (1993); and the Kap Stewart-type complex is based on Dam and Surlyk (1992).



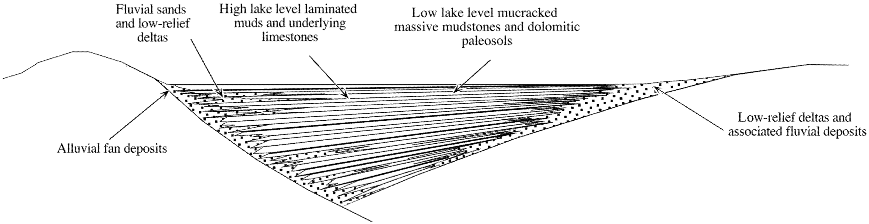
RICHMOND-TYPE LACUSTRINE COMPLEX
(± 2° N & S Latitude)



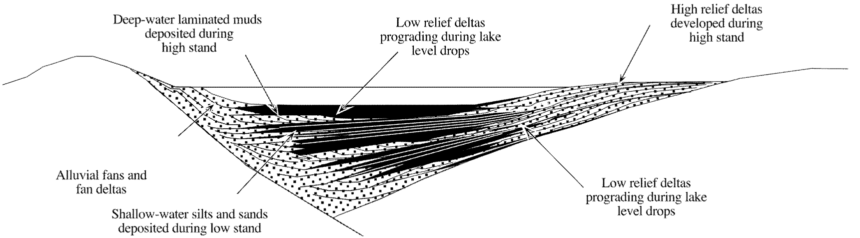
NEWARK-TYPE LACUSTRINE COMPLEX
(2°- 12° N Latitude)



FUNDY-TYPE LACUSTRINE COMPLEX
(10°- 33° N Latitude)



FLEMING FJORD-TYPE LACUSTRINE COMPLEX
(24° - 38° N Latitude)



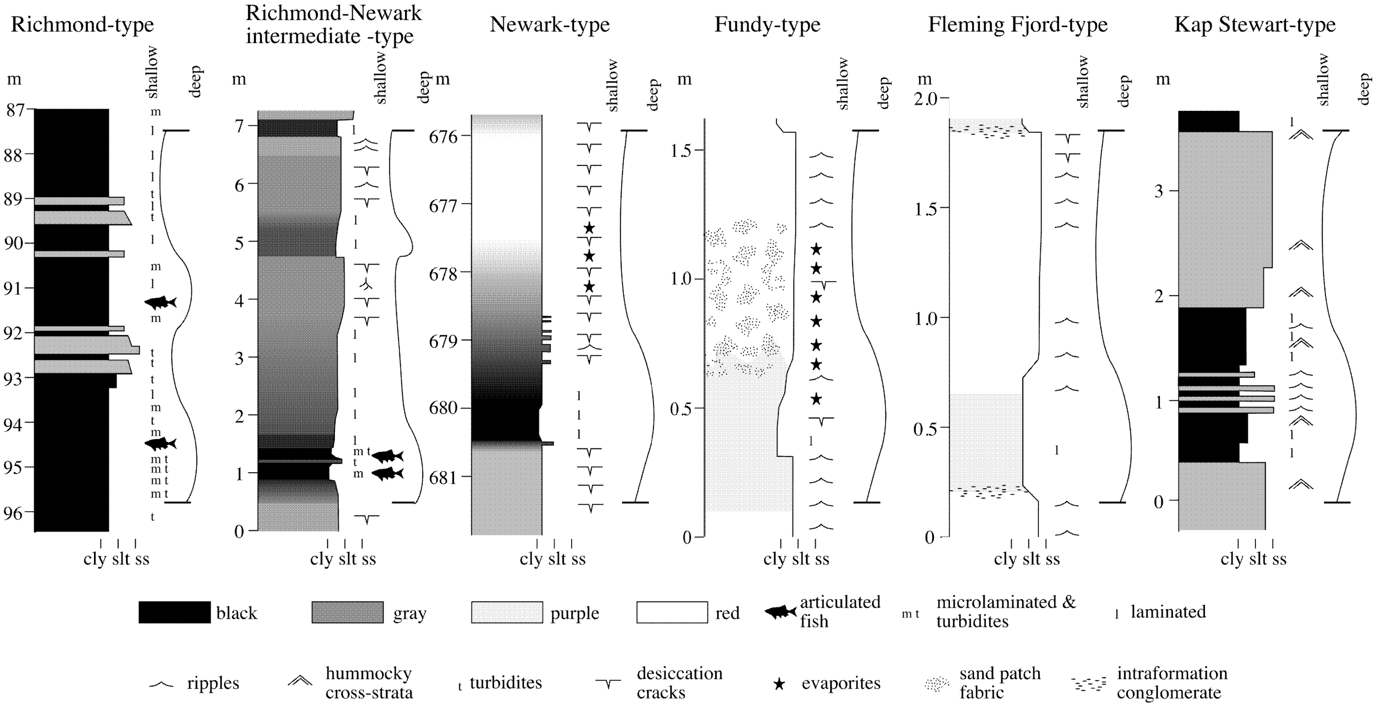
KAP STEWART-TYPE LACUSTRINE COMPLEX
(> 35° N Latitude)

found in the Deep River, Dan River, Taylorsville, Culpeper, Gettysburg, Newark, Hartford, Deerfield, and Argana basins. Those of the Deep River, Dan River, Taylorsville basins are transitional to Richmond-style sequences, while the Argana basin is transition between Newark- and Fundy-style sequences.

Fundy-type lacustrine sequences are characterized by evidence of very low synsedimentary topography and are highly cyclical, as in Newark-type sequences (Figs. 4c, 5). However, Fundy-type sequences virtually lack black and gray shales, and microlaminated black shales being completely absent. Instead, such sequences are dominated by red massive mudstones and eolianites, with abundant evaporites, which can include massive beds of sulfates and halite. A very common facies is termed sand-patch massive mudstone, which is a muddy eolianite that accumulated on an efflorescent evaporitic crust (Smoot and Olsen 1988). Thick and widespread eolian dune sequences are also present (Hubert and Mertz 1980). Significant bodies of coarse clastics tend to be limited to the margins of the basins, although abundant, thin tabular "sheet flood" sandstones extend far into the basin. Fundy-type lacustrine sequences have been identified for certain in the Fundy and Argana basins, but are probably more widespread, most likely occurring in other basins in Morocco, the Scotian Shelf, Grand Banks, Iberia, and in older Triassic strata in Europe, although we have not confirmed their presence through first-hand observation.

Fleming Fjord-style lacustrine sequences are similar to Fundy-type sequences in lacking synsedimentary relief and in being dominantly red-bed sequences (Figs. 4d, 5, 6). However, mudcracked massive mudstones and bioturbation (both by invertebrates and roots) are more common, while evaporites and eolianites are rarer, although occasionally present, especially in more southern examples. Thin, stromatolitic carbonates, dolostones, and ripple-laminated sandstones are also present along with rare, thin coals. This type of sequence is characterized by common evidence of liquefaction, which apparently mired prosauropod dinosaurs (Sander 1992, Jenkins et al. 1994). The best described examples of this type of Fleming Fjord-style lacustrine sequence are the Trossingen (Knollenmergel) and Arnstadt (Steinmergelkeuper) formations of the Germanic basin (Seegis 1993, Bachmann et al. 1998, Beutler 1998, Reinhardt and Ricken 1998, Kellner 1998) and the Fleming Fjord Formation of the Jameson Land basin in east Greenland (Clemmensen 1980). However, Fleming Fjord-style lacustrine sequences are almost certainly more widespread than this list would indicate and probably characterize portions of most of the Triassic basins of northern Europe.

Fig. 5. Representative sections of lacustrine cycles in the different styles of lacustrine complexes with each cycle shown corresponding to a 20 ky climatic precession cycle. Richmond-type is from the VAGO no. 1 core, Richmond basin, Vinta beds, near Manakin, VA, USA; Richmond-Newark- intermediate type is from outcrop (cycle in Dan River section in figure 7 labeled with asterix), Solite Quarry, Leaksville Junction, VA, USA; Newark-type is the upper part of the lower Perkasie Member of the Passaic Formation, Newark basin from the Rutgers no. 1 core, Pistcataway, NJ, USA; Fundy-type lacustrine cycle is based on Smoot and Olsen (1988); Fleming Fjord-type is based on Clemmensen et al. (1998); and Kap Stewart type is based on Dam and Surlyk (1993).


Richmond-type
Richmond-Newark intermediate -type
Newark-type
Fundy-type
Fleming Fjord-type
Kap Stewart-type
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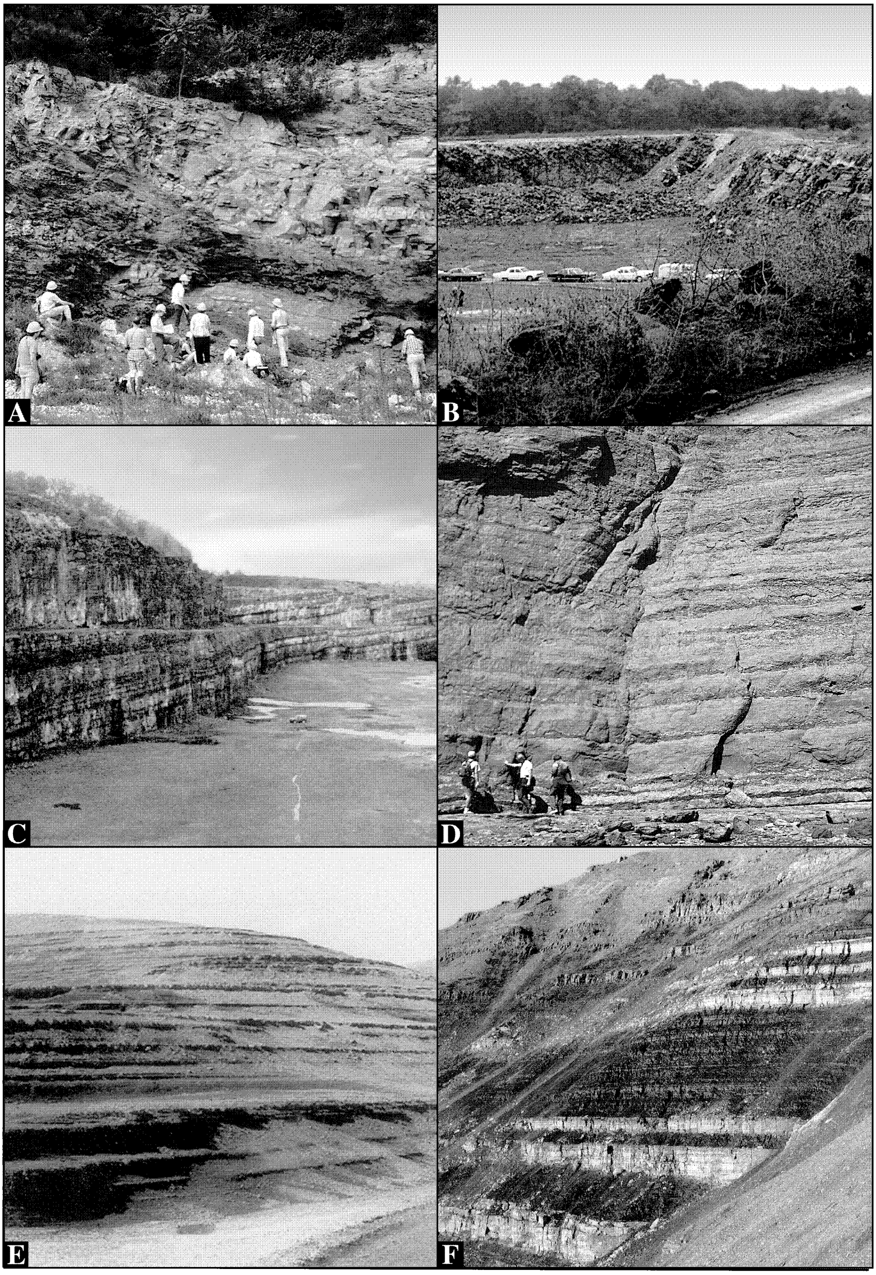
A
B
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D
E
F

Kap Stewart-type lacustrine sequences resemble Richmond style sequences in abundance of sand and evidence of higher-relief structures such as deltas (Figs. 4e, 5). However, aqueous wind-dominated sediment reworking is much more prevalent (Dam and Surlyk 1992) and coals are much more abundant than in Fleming Fjord-style sequences. While black shales are very common , microlaminated units, with their characteristic taphocoenesis have not been specifically described. This type of sequence is apparently very common in Northern Europe and East Greenland having been described from the Danish-Polish basin of Denmark, Sweden, and Poland (Pienkowski 1984, Norling et al. 1993), the Haltenbanken area (Hollander 1984), and East Greenland (Dam and Surlyk 1992, 1993). It is not known how far north the Kap-Stewart type sequences extend. We note that the presence of coals at high latitudes is to be expected under the high precipitation regimes successively predicted by some global climate models for a "hot house" Triassic world (Kutzbach 1994). We also note that some portions of Kap Stewart-type sequences contain some beds with marine invertebrates (Germanic and Danish-Polish basins), indicating at least some incursions of marine waters.

These lacustrine sequences generally characterize very large portions of the basin sequences and different types of sequences can follow each other in vertical succession. The vertical succession of lacustrine types follows the general climatic pattern previously outlined. Richmond type sequences developed in the humid equatorial tropics; Newark type formed in the seasonally and millennially arid transition zone into the arid tropics; Fundy-type sequences were deposited within the arid tropics; Fleming Fjord-type sequences formed in the transition to the temperate zone; and Kap Stewart-type sequences formed in the humid temperate zone under "hot house" conditions. The latitudinal arrangement of lacustrine types basically reflects the large-scale zones of differing precipitation/evaporation ratios. As the basins translated north with central Pangea, the major lacustrine sequence type changed with the passage into different climate zones. Examples in which one sequence type unambiguously follows another in vertical sequence within a single basin include the Taylorsville basin of Virginia (Richmond- up into Newark-type; LeTourneau 1999), the Argana basin, Morocco (Newark- up into Fundy-type; Olsen 1977), and the Jamesonland basin, Greenland (Fundy- up through Fleming Fjord- and Kap Stewart-type, this paper).

Fig. 6. Photographs of different lacustrine styles. A, Richmond-type lacustrine complex, Richmond basin, lower Vinita beds, Boscabel Quarry, Manakin, VA, USA; B, lacustrine complex transitional between Richmond- and Newark-types, Dan River basin, upper member of the Cow Branch Formation, Solite Quarry, Leaksville Junction, VA, USA (section shown corresponds to upper 40 m of Dan River section in figure 7) (photo courtesy of C.H. Gover); C, Newark-type lacustrine complex, Newark basin, Lockatong Formation, Eureka Quarry, Eureka, PA, USA; D, Fundy-type lacustrine complex, Fundy basin, upper Blomidon Formation, Blomidon Provincial Park, Blomidon Nova Scotia, Canada; E, Fleming Fjord-type lacustrine complex, Tait Bjerg beds, Fleming Fjord Formation, north of Macnight Bjerg Jameson Land, East Greenland, from Clemmensen et al. (1998); F, Kap Stewart-type lacustrine complex, Kap Stewart Formation, Rununkeldal section, Jamesonland, East Greenland, from Dam and Surlyk (1993).

Orbitally forced lacustrine cycles

Although much work remains, the broad outline of the latitudinal variation in orbital forcing in Triassic-Jurassic Pangea is evident. On first principles, we would expect the tropics to be dominated by precession cycle-related orbital forcing (Short et al. 1991). However, this forcing should be reflected as a prominent 10 ky cyclicity near the equator, mirroring the twice annual passage of the sun overhead (Crowley 1992). On the other hand ~20 ky cyclicity should dominate further north and south towards the temperate regions where obliquity-related forcing should become more prominent. To first order, this pattern of orbital forcing is observed in these Triassic-Jurassic lacustrine sequences. The details of orbital forcing can be seen using the Newark basin time scale and correlating other basin sections using magnetostratigraphy, even though the chronostratigraphy of the other basins is not known as well as that of the Newark basin.

Richmond-type sequences have a cyclicity in which each ~20 ky cycle has two distinct high stand intervals, suggesting a roughly 10–15 ky cyclicity, while the typical precession related ~100 and 413 ky period eccentricity cycles are also present. Newark-type lacustrine sequences tend to have only a well developed single high stand per ~20 ky cycle (Fig. 6). Within relatively deeper portions of basin sections with Richmond-style sequences, we hypothesize deposition in lakes which alternated on millennial time scales between being perennially deep and chemically stratified during their high stands, and shallower with at least seasonal oxygenation during their low stands (Fig. 6).

Sequences intermediate between Richmond- and Newark-type, such as those in the Cow Branch Formation of the Dan River basin, also show a strong 10–15 ky cyclicity (Fig. 6), and a comparison of Carnian age Dan River and Newark coeval sections is shown in Figure 7. In the Dan River sequence depicted, the lake was deep and perennially stratified during at least one of the two high stands, and during the low stands usually dried out completely, spending significant amounts of time as playa. In contemporaneous Newark basin lakes of the Lockatong Formation, some lakes became deep enough to be perennial stratified during high stands, but all dried out completely during single 20 ky cycles with most of the time being spent as playas. Playa waters often became saline with deposition of evaporites.

Norian-age, Newark-type lacustrine sequences of the Culpeper basin have better developed 20 ky cyclicity than precisely correlative strata of the Newark basin (Fig. 8), commensurate with the more southern position of the former basin. In the deepest water cycles, the lakes became deep enough to become chemically stratified during their high stands. Usually, however, the lakes became deep enough to be seasonally stratified only. During low stands the lakes became playas with only very minor evaporite deposition. The dry lake beds frequently became vegetated. Coeval Newark basin lakes had much more evaporite deposition, less vegetation, and the high stands almost never were deep enough to allow chemical stratification.

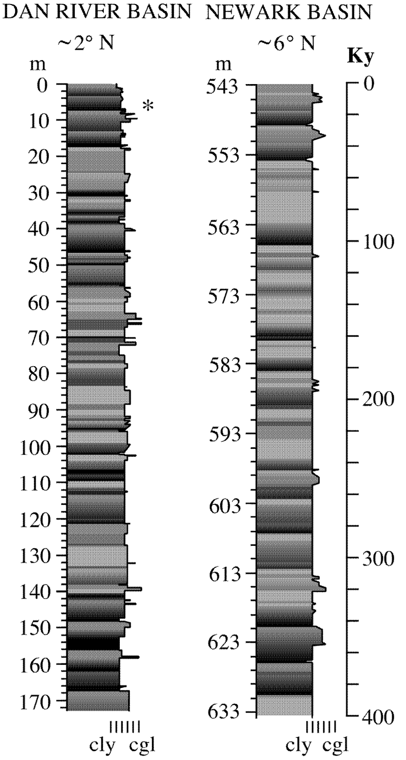

Fig. 7. Comparison of contemporaneous sections, based on polarity stratigraphy (Kent and Olsen 1997), from the Dan River (upper member of the Cow Branch Fm.) and Newark (Lockatong Fm.) basins. Dan River Basin section is the Solite Quarry, Leaksville Junction, VA, USA (asterisk indicates position of cycle shown in figure 5); Newark basin section is from the Nursery no. 1 core, near Titusville, NJ, USA. See figure 5 for key to rock color.

In the Fundy basin, preliminary magnetostratigraphic correlations indicate the exposed sections are very condensed (Fig. 8) and appear to have minor disconformities or intervals of very low sedimentation rate, making spectral analysis difficult to interpret. Nonetheless, it does appear that the 20 ky cyclicity is still prominent (Figs. 6, 8). There may also be some indication of the ~40 ky obliquity cycle as well. The highest lake levels were relatively shallow by Newark basin standards, never becoming perennially stratified, and most Fundy lakes were playas at their deepest. During low stands all of the lakes dried out completely. The water table remained high, however, and evaporitic crusts formed during the dominant intervals of lake desiccation. Occasionally bedded evaporites formed, and vegetation was nearly absent except perhaps at the playa margins.

Precessional forcing was evidently still strong during the deposition of Fleming Fjord-type sequences (Figs. 6, 8) (Kent and Clemmensen 1996). However, apparent obliquity forcing is much stronger than in more southern styles of lacustrine sequences (Clemmensen at al. 1998). These lakes also never became perennially stratified and remained shallow. They did not, as a rule become saline during low stands, and were often heavily vegetated instead (Seegis 1993).

There is no magnetostratigraphy for Kap Stewart-type lacustrine sequences, and there is no calibration of the sedimentary cycles. However, Dam and Surlyk

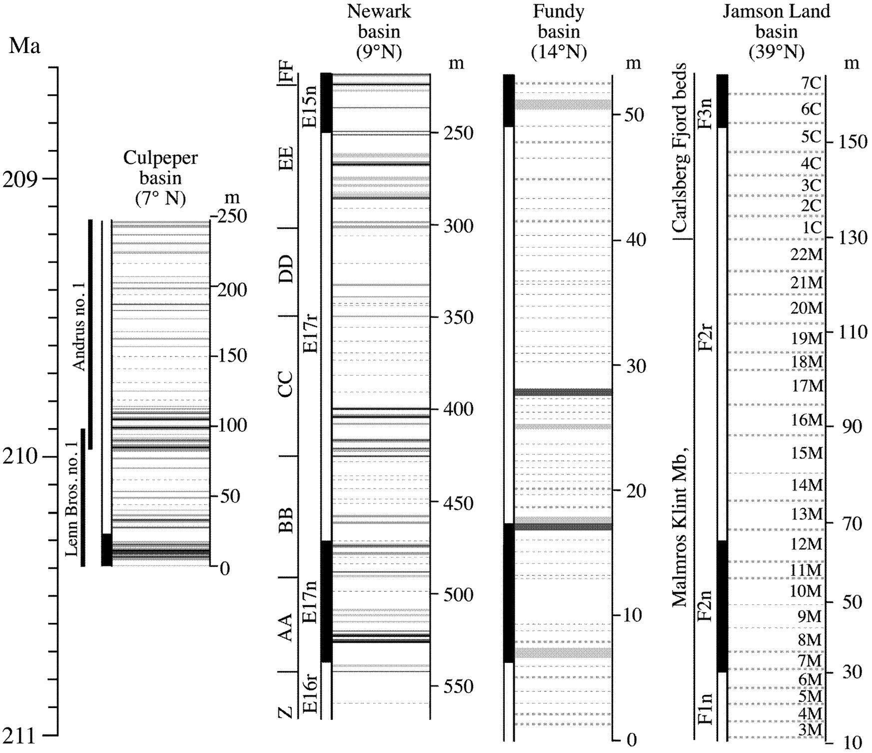

Fig. 8. Comparisons of correlative sections of the Culpeper, Newark, Fundy, and Jameson Land basins. Culpeper section is from the Lenn Bros. no. 1 and Andrus no. 1 cores of the Bull Run Formation (Balls Bluff Siltstone), Newark section is from the Somerset no. 1 core of the middle Passaic Formation (E16r-E18n are magnetic polarity zones, and Z-FF are member names from Kent et al. 1995 and Olsen et al. 1996b), Fundy basin section is based on outcrop (Blomidon area, Nova Scotia) correlated by lithostratigraphy to the GAV-3 core which is the source of the magnetostratigraphy; Jameson Land basin section is based on Kent and Clemmensen (1996) and Clemmensen et al. (1998) (3M-7C are Clemmensen's designations of ~100 ky cycles). See figure 5 for key to rock color.

(1992, 1993) do suggest Milankovitch control for the cyclicity. We would predict a prominent 40 ky cyclicity along with at least some precessional forcing for the high frequency cycles. Dam and Surlyk (1992, 1993) suggest that during high stands the lakes were perennially chemically stratified and during low stands were characterized by extensive delta progradation far into the lake interior, with remaining lakes being shallow with at least occasionally oxygenated bottom. The lakes sometimes dried out and became densely vegetated and swampy.

Milankovitch theory predicts differences in phase between high stand events of roughly 5 ky for the lake high stands between the equator and tropic latitudes (~23.5°) and a 10 ky phase difference between the tropics of each hemisphere.

There is no theoretical reason why these phase differences should not be observable within these basin sequences. However, recognizing the phases of the cycles requires very fine sampling of specific polarity zone boundaries across different basins, which has not yet been done. A possible complication would be run off from a broad enough latitudinal swath that such out-of-phase wet intervals contributed water to a single basin. Watershed complications of this type might indeed have existed in some of the Triassic-Jurassic Pangean rift lakes as is now true of the seasonal cycle in Lake Tanganyika (Degens et al. 1971). It is interesting to note that currently we have a higher level of temporal resolution of Triassic Pangean tropical lake level fluctuations across latitudes then we have for Pleistocene tropical African rift lakes.

Global context

On a global scale, most of the apparent large climate changes seen in early Mesozoic basins can be explained by the northward drift of Pangea (e.g. Dickenson 1989, Dubiel 1989). Thus, the drying seen in the classic Colorado Plateau sequence of the Chinle and Glen Canyon groups in the Western US is parallel to that seen in eastern North America. Similarly, the drying seen in the Late Triassic and Early Jurassic sequences of the Karoo basin, and in Argentine and Brazilian basins, can be explained by their drift from the south temperate regions into the southern arid belt.

Correlation of existing Late Triassic marine paleomagnetic polarity sequences with the Newark basin time scale remains problematic (see Kent et al. 1995, Gallet 1993). The correlation problems are probably attributable to the very condensed nature of the marine sections sampled so far. Hopefully this problem will be remedied soon, for the lack of this correlation prevents comparison of rift lake and eustatic sea level fluctuations.

It is worth noting that there are significant differences between the climatic patterns described here and the predictions of existing global climate models (e.g. Pollard and Schulz 1994, Wilson et al. 1994). The published comparisons between these models and compiled geological data is especially poor, although some are much better than others (e.g. Kutzback 1994). While there are many potential reasons for poor match between putative observations and model predictions, at least in part these problems can be ascribed to the use of outdated paleomagnetic data, especially very poor time control, and poor climate proxies. In this paper we have tried to show that very high levels of temporal and geographic resolution are possible in these ancient strata. Triassic-Jurassic basins are unusual in that many maintained relatively continuous continental sedimentation for millions of years and are distributed over much of the globe. The combination of cyclo- and paleomagnetic stratigraphy that can be recovered from these basins provides unparalleled potential for very large-scale synoptic views of climatic, tectonic, and biotic evolution at Neogene levels of temporal resolution for a pivotal time in Earth history. Extension of these techniques globally would provide a sorely needed defensible base for model-data comparisons (e.g. climate model "validation") and a much fuller understanding of the evolution of global climate.

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