RESULTS FROM PRIOR NSF SUPPORT

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Mesozoic Continental Tetrapod Diversification and Extinction in Eastern North America: BSR 87-17707; 3/1/88-8/31/90; $135,272; Paul E. Olsen & Hans-Dieter Sues.

This project examined biotic diversification and extinction in the Newark Supergroup of eastern North America, documenting the faunal transitions through the Late Triassic and Early Jurassic. Special attention was paid to Carnian and Early Jurassic age strata to try to remedy the lack of footprint and bone assemblages. Specimens were collected from three independent taphofacies: 1) fluvial-terrestrial taphofacies; 2) tetrapod lake-margin ichnofacies; and 3) deep lake tetrapod taphofacies. After completion of the Newark Basin Coring Project (EAR 89-16726 to P. E. Olsen and D. V. Kent - below) it is now possible to relate all of the finds to the high-resolution time and geomagnetic polarity scale that resulted from that project. We were extremely fortunate in discovering an exceptionally rich synapsid-dominated assemblage of Carnian age in the Richmond basin (Tomahawk Assemblage), which was equatorial during that time, filling a major gap in our understanding of Triassic diversity. We also expanded the collections of bones from just above the Triassic-Jurassic boundary in Nova Scotia, making it the richest assemblage of that age in the world. This material falsified the hypothesis that the Triassic-Jurassic mass extinction was spread though a significant part of the Jurassic. Finally, a number of superb Carnian-age footprint assemblages were recovered and these showed that there was no major Carnian-Norian faunal break. Related topics include the morphology of the vertebrates found during the work, cyclostratigraphy, geochronology, palynostratigraphy, and lithostratigraphy. This grant partially supported the Ph.D. theses of S. Fowell and R. Schlische.

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Milankovitch Forcing of Continental Monsoons Across the Equator of Pangea: ATM 93-17227; 5/1/94 - 10/31/97; $387,243; Paul E. Olsen & Dennis V. Kent.

In order to partly remedy our very poor understanding of long term behavior (10^4-10^6 years) of tropical continental climate in response to orbital forcing, we investigated Triassic lacustrine records from rift basins that extended from the equator to about 37° N paleolatitude. We focused on two intervals constrained by bio- and magnetostratigraphy. The oldest (218 - 224 Ma) was examined in the Dan River basin (NC, 1 ° N paleolatitude) and the 500 km distant Newark basin, (NJ, 4° N). Lake level cyclicity changes from dominant ~10 ky to ~20 ky cyclicity from south to north. Evaporites, absent in the south, are present in the north. Though predicted by celestial mechanics, this pattern has not previously been observed in continental environments, although there are strong hints from continental proxies in Quaternary marine records. The younger interval (207 - 211 Ma) was examined over a 3000 km transect. Strong ~20 ky cyclicity in red beds in the Culpeper Basin (VA, 6° N) gives way to evaporite-bearing ~20 ky cycles in the Newark basin (9°N) and eolian/evaporite cycles with ~20 and ~40 ky cyclicity in the Argana (Morocco, 12° N) and Fundy basins (Nova Scotia, 13°). Obliquity-forced ~40 ky cyclicity remains present in the non-evaporite-bearing Fleming Fjord Fm. (E. Greenland, 37° N). All areas show strong effects of the 100, 400, and 2000 ky precession modulating cycles as well. We believe this pattern of local forcing is typical of other continental tropical setting including the present. The Ph.D. theses of Peter LeTourneau and Mary Ann Malinconico have been partly supported by this grant.

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PROJECT DESCRIPTION

This proposal seeks funds to develop a high-resolution chronologic, stratigraphic, and paleogeographic framework for the southernmost exposed Triassic rift basins in eastern North America. This has become necessary because of the exciting discovery of unexpectedly rich, seemingly endemic tetrapod assemblages from these basins, that suggest new interpretations of the pattern of Late Triassic faunal evolution.

Introduction and Need For Project

The tempo and mode of Triassic continental faunal change and biogeographic patterns were remarkable in three respects: **1)** *the origin of the major groups of continental vertebrates occurred during the Triassic* (Fraser and Sues, 1994); **2)** *the period began and ended with two of the five largest mass extinctions of the Phanerozoic* (Sepkoski, 1990; Wing and Sues, 1992); and **3)** *despite continental unity during the Triassic, strong faunal (and floral) provinciality existed at the close of the period, but was nearly obliterated by the earliest Jurassic* (Olsen and Galton, 1984; Shubin and Sues, 1991).

Understanding of these major biotic patterns has been hampered by poor temporal and geographic constraints, although there have been considerable advances in recent years. In particular, the humid equatorial region of Late Triassic Pangea has remained very poorly known, despite the fact that, presently, equatorial tropics have the greatest terrestrial vertebrate biodiversity (Gaston, 2000), presumably reflecting the positive relationship between biodiversity and potential evapotranspiration (Currie, 1991). Indeed, the inferred Triassic climatic pattern itself has been muddled with quite a few analyses denying the existence of any humid equatorial zone during the Early Mesozoic (e. g., Zeigler et al., 1993), an assessment apparently based on previously unappreciated uncertainties in temporal correlation and geographic position (Kent and Olsen, 2000b). It is within this context that we propose a litho-, cyclo-, and magneto-stratigraphic study of newly discovered diverse terrestrial vertebrate assemblages in North Carolina and Virginia, in what is apparently the best available equatorial record of continental faunal change for the Late Triassic.

The continental record of the equatorial region of Pangea is represented in eastern North America by the southernmost Newark Supergroup rifts, particularly the Deep River, Dan River, Richmond, and Taylorsville basins of North Carolina and Virginia (Fig. 1). Commercial coal mining during the early to mid-19th century resulted in the discovery of several now classic (although enigmatic) vertebrate assemblages (Redfield, 1837; Emmons, 1856, 1857, 1858). Recent discoveries in Late Triassic age strata of eastern North America in these basins show that skeletal remains of tetrapods are not only far more abundant than previously known, but are actually common, diverse, and well preserved (Figs. 2 and 3). The new discoveries, coupled with the classic finds, have surprising implications for both long-held and recent biogeographic and biostratigraphic hypotheses. Specifically, the new data suggest a well developed humid equatorial region with a distinct and temporally persistent tetrapod fauna. These basins and their contained fossils comprise the only outcropping continental records constrained to be in the equatorial zone of Triassic Pangea.

The apparent endemism of this fauna is a very significant challenge to traditional biostratigraphic approaches to correlation, and requires independent methodologies for correlation of the different stratigraphic levels in the various basins, both with each other, and with areas outside the equatorial region such as the Newark basin (Fig. 1) and the Chinle Group of the western United States.

We have demonstrated in previous NSF-funded work that a combined cyclo- and magneto-stratigraphic approach to correlation within the Newark Supergroup is capable of Neogene-levels of temporal correlation over thousands of kilometers (Figs. 4 & 5) (Kent and Clemmenson, 1996; Olsen, 1997; Olsen and Kent, 2000; Kent and Olsen, 1997, 2000b). We will use this methodology in cutting through the Gordian Knot of equatorial biogeographic provinciality and long distance biostratigraphic correlation for these equatorial basins. Specifically, we propose to develop such integrated chronostratigraphies for the southernmost of the Newarkian rifts: the Deep River, Dan River, Richmond, and Taylorsville basins. Without such independent means of correlation, recognition of biogeographic and paleoclimatic patterns is essentially impossible.

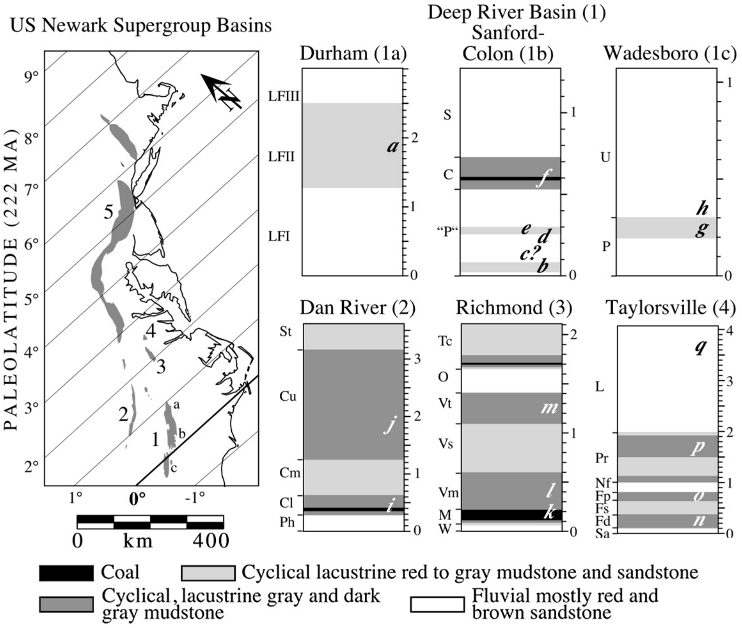


Figure 1. Major basins and basin sections of the paleoequatorial part of the Newark Supergroup. Left, map of basins (gray); 1, Deep River basin (a, Durham subbasin; b, Sanford subbasin; c, Wadesboro subbasin); 2, Dan River basin; 3, Richmond basin; 4, outcropping part of Taylorsville basin; 5, Newark basin. Right, diagrammatic sections of the basins 1-4. Lithologic units are as follows. Durham basin: LFI, LFII, LFIII - Lithofacies assemblages I-III. Sanford subbasin and Colon cross-structure: "P," Pekin Fm.; C, Cumnock Fm.; S, Sanford Fm. Wadesboro basin: P, type Pekin Fm.; U, undifferentiated. Dan River Basin (including Danville basin): Ph, Pine Hall Fm.; Cl, lower member of the Cow Branch Fm.; Cm, middle member of Cow Branch Fm.; Cu, upper member of Cow Branch Fm.; St, Stoneville Fm.. Richmond basin (from LeTourneau et al., 2000): W, "Winterpock fm."; M, "Midlothian fm."; Vm, "Manakin member" of Vinita Fm.; Vs, "Swift Creek member" of Vinita Fm.; Vt, "Tomahawk member" of Vinita Fm.; O, Otterdale Fm.; Tc, "Turkey Creek fm.". Taylorsville basin (from LeTourneau et al., 2000): Sa, "South Anna fm."; Fd, "Deer Creek member" of Falling Creek Fm.; Fs, "Stagg Creek member" of Falling Creek Fm.; Fp, "Poor Farm member" of Falling Creek Fm.; Nf, Newfound Fm.; Pr, "Port Royal fm."; L, "Leedstown fm.". Major fossil assemblages and occurrences; ***a***, Genlee tetrapod and fish assemblage; ***b***, Moncure floral assemblage; ***c?***, new Merry Oaks assemblage (exact horizon, uncertain); ***d***, Pomona tetrapod assemblage; ***e***, Boren floral assemblage; ***f***, classic Cumnock tetrapod and fish assemblage of Emmons (1856, 1857); ***g***, "lower Pekin" tetrapod and fish assemblage; ***h***, upper Pekin tetrapod assemblage; ***i***, lower Cow Branch tetrapod and fish assemblage; ***j***, upper Cow Branch tetrapod and fish assemblage; ***k***, "productive coal measures" flora; ***l***, Vinita fish assemblage; ***m***, Tomahawk tetrapod, fish, and floral assemblage; ***n***, lower Falling Creek fish assemblage; ***o***, upper Falling Creek tetrapod, fish, and floral assemblage; ***p***, upper Port Royal *Turseodus* occurrence; ***q***, upper Leedsville *Aetosaurus* (*Stegomus*) occurrence.

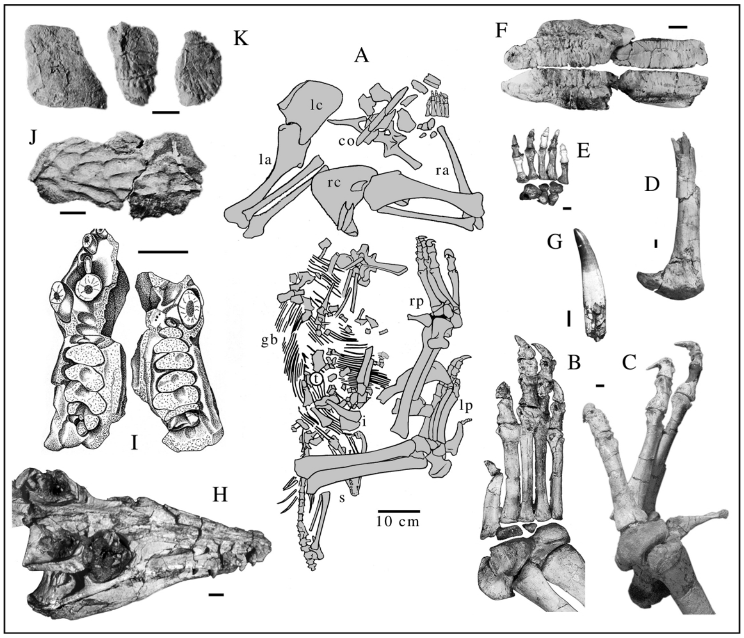
Faunal Assemblages

There are three important new vertebrate assemblages that triggered this proposal; the Tomahawk, the Genlee, and the New Hill assemblages. These have major implications for the rates and geographic pattern of Triassic tetrapod diversification and extinction.

Tomahawk: The Tomahawk assemblage from the Richmond basin (Table 1), was worked extensively in the late 1980s (Sues and Olsen, 1990), although its full importance has only been realized within the last few months. The Tomahawk assemblage comes from the upper Vinita Formation in the mostly-gray, cyclical, largely lacustrine "Tomahawk member" of LeTourneau (1999, 2000). This was the first significant tetrapod assemblage found in the Richmond basin. Its most surprising aspect is that it is dominated by the basal traversodont cynodont *Boreogomphodon jeffersoni* Sues and Olsen 1990 represented by hundreds of specimens (Table 1). At least two other cynodonts are present, one of which is clearly *Microconodon tenuirostris* (represented by several mandibles, teeth, and several partial cranial fragments). Elsewhere, *Microconodon* is known only from the single type dentary from the Cumnock Formation of the Sanford subbasin of the Deep River basin. The other cynodont appears similar to *Tricuspes* from European Rhaetian age strata. A significant number of other non-synapsid tetrapod taxa are present, and most are in the process of being described.

Genlee: The Genlee assemblage was discovered in 1995 by a team from the University of North Carolina at Chapel Hill (Peyer, et al., 1999; Sues et al., 1999; Carter et al., 2000), in an active clay mine in Genlee, North Carolina in Lithofacies II of the Durham subbasin of the Deep River basin (Table 1). This locality has long been known for its unusual assemblage of aquatic invertebrates and vertebrates (Olsen in Bain and Harvey, 1977), that include the stagonolepid *Aetosaurus* (*Stegomus*) (sensu Lucas et al., 1998), and an indeterminate phytosaur and

Figure 2. New rauisuchian and intimately associated tetrapods from Genlee, North Carolina (from Carter et al., 2000). Scale is 1 cm except as noted. **A-F,** new rauisuchian closely related to *Postosuchus* (A, partial skeleton as reconstructed in situ; **B**, **C**, left and right pes; **D**, right partial pubis; **E**, right manus; **F**, two pair of cervical osteoderms; **G**, isolated tooth with root; s, sphenosuchian skeleton; **rp**, **lp**, right and left pes; **i**, associated stagonolepid; **t**, traversodont bones; **gb**, gastralia basket; **ra**, **la**, right and left forelimbs; **rc**, **lc**, right and left scapulacoracoids; co, cervical osteoderms); **H**, skull of nearly complete, articulated new sphenosuchian crocodyliomorph found under belly and left hindlimb of rauisuchian; **I**-**K**, examples of gastric contents of rauisuchian (**I**, snout of traversodont cycnodont *Plinthogomphodon herpetarius* [from Sues et al, 1999]; **J**, fragmentary pectoral girdle element of temnospondyl amphibian; **K**, osteoderms of stagonolepid suchian cf. *Aetosaurus* (*Stegomus*) sp.).



metoposaur. However, the new discovery consists of a new articulated rauisuchian with stomach contents and a new sphenosuchian that may have died while in the act of predation (Fig. 2). Especially unusual is that the stomach contents of the rauisuchian include elements of two synapsids (*Plinthogomphodon herpitarius* and cf. *Placerias* sp.), a fairly well preserved *Aetosaurus* (*Stegomus)*, and a fragmentary temnospondyl amphibian (Fig. 2). Again, synapsids are surprisingly prevalent in the assemblage.

New Hill: The New Hill assemblage was discovered less than three years ago by a team from the North Carolina Museum of Natural Science (NCMNS), in the middle Pekin Formation (as mapped by Reinemund, 1955 and Bain and Harvey, 1977) of the Colon cross-structure of the Deep River basin near New Hill, North Carolina (Vince Schneider, NCMNS, pers. comm., 2000). The most common diagnostic elements in this assemblage are synapsids and stagonolepids (Table 1). A small traversodont is represented by at least five skulls of varying completeness, together with a partial skeleton and isolated bones of a dicynodont (probably *Placerias*) (Fig. 3). Stagonolepids are represented by two articulated partial skeletons (one of which appears to be *Aetosaurus* [*Stegomus*]) and many isolated osteoderms. Most of this material awaits complete preparation, so genus-level identifications are tentative.

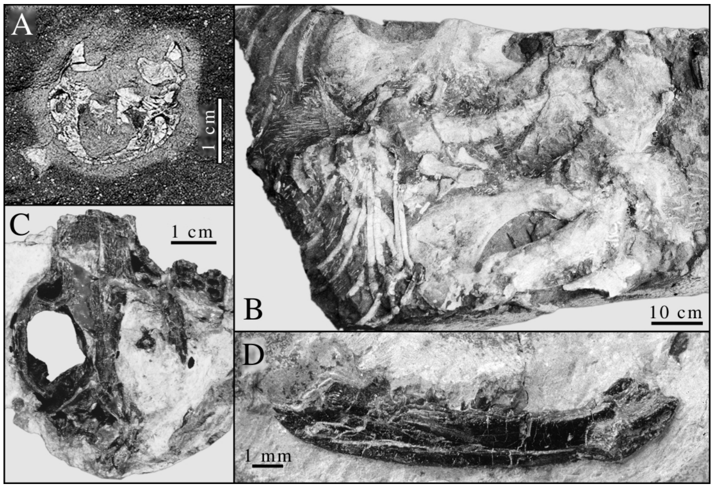


Figure 3. Examples of new faunal elements from Deep River and Richmond basins. **A-B**, New Hill locality, Deep River basin. **A**, unidentified unprepared traversodont cycnodont; **B**, partially articulated dicynodont cf. *Placerias*; **C-D**, Tomahawk locality, Richmond basin. **C**, nearly complete cranium of traversodont cycnodont *Boreogomphodon jeffersoni*; **D**, lingual view of nearly complete dentary of *Microconodon* cf. *M. tenuirostris*.

Other Assemblages: A series of other very important tetrapod assemblages have been recovered from other units within the Deep River, Dan River, and Taylorsville basins (Table 1); three of these are especially noteworthy. The first consists of the classic assemblage from the Cumnock Formation of the Deep River basin originally described by Emmons (1856, 1857, 1858) and Osborn (1886). Most important in this largely aquatic assemblage are the phytosaur *Rutiodon carolinensis* and the advanced cynodonts *Dromatherium* and *Microconodon* (Table 1). A more recently discovered assemblage comes from the middle Pekin Formation of the Pomona and Boren pits in Gulf, North Carolina (Baird and Patterson, 1968). This assemblage is noteworthy in producing the dicynodont synapsid *Placerias*, as well as a variety of suchians and footprints (reviewed in Olsen et al., 1989; Huber et al., 1993; Lucas, 1998; Olsen and Huber, 1996). A final important assemblage was recovered in the 1970's by R. Weems (USGS) in the "Poor Farm member" of the Falling Creek Formation of the Taylorsville basin (LeTourneau et al., 2000). This assemblage consists of a partial skeleton of *Doswellia kaltenbachi*, also known from the Tomahawk assemblage, as well as probable phytosaur bones and fish remains (Table 1). Recent prospecting by one of us (PML) has shown that numerous, as yet unidentified, tetrapod bones occur in outcrops of this member. Other vertebrate data from the southern Newark Supergroup basins are given in Table 1.

Biogeographic Patterns: Vertebrates from these assemblages have the potential to shed light on a striking and long-standing paleobiological conundrum revolving around the apparent presence of strong faunal and floral provinciality during the Late Triassic - a time when continenta1 unity would imply that cosmopolitan assemblages should be expected. Two basic faunal provinces have long been recognized: a Laurasian assemblage, dominated by phytosaurs and metoposaur amphibians, and a Gondwanan assemblage dominated

Table 1: Vertebrates from the Southern Newark Basins Abbreviations as in Fig 1.

Taxon	Assemblage
Chondrichthyes	
Lissodus spp.	a m
Chondrichtyes indet.	i j
Osteichthyes	
Actinopterygii	
Paleoniscidae	
Turseodus spp.	a j p
Redfieldiidae	
Dictyopyge macrurus	k l m n o
Synorichthyes sp.	a f g i j
Cionichthyes cf. *greeni*	l
Holostei	
Semionotus sp.	a m n j
Telosteii	
Pholidophoridae indet.	j
Coelacanthini	
Pariostegus myops	f j
Coelacanthini indet.	a f g i j m n
Temnospondyli	
Metoposauridae indet.	a
Dictyocephalus elegans	f
Temnospondyli indet.	a
Procolophonia	
Gomphiosauridion baileyae	m
Xenodiphyodon pteraios	m
Sauropsida	
cf. Coelurosauravidae	j
Sphenodontidae indet.	m
Lepidosauria spp. indet.	m
cf. Choristodera indet.	m
Archosauromorpha	
Tanystropheidae	
Tanytrachelos ahynis	g j
Archosauromorpha indet.	
Doswellia kaltenbachi	o m
Uatchitodon kroehleri	m
Archosauria	
Parasuchia	
Rutiodon carolinensis	f i
Phytosauria indet.	a c d f g h i j
Suchia	
Euscolosuchus olseni	m
Sphenosuchia n. sp.	a
Rauisuchia n. gen. et sp.	a
Rauisuchia indet.	c d f
cf. *Aetosaurus* (*Stegomus*)	a c q
Longosuchus sp.	c
Desmatosuchus sp.	g
Stagonolepidae indet.	c
Dinosauria	
Ornithischia	
Pekinosaurus olseni	g
Ornithischia indet.	m f
Synapsida	
Cynodontia	
Boreogomphodon jeffersoni	m
Plinthogomphodon herpetaris	a
Traversondontidae indet.	c
Microconodon tenuirostris	m f
Dromatherium sylvestre	f
cf. *Tricuspes*	m
Dicynodontia	
Kannemeyeriidae	
Placerias sp.	d c a

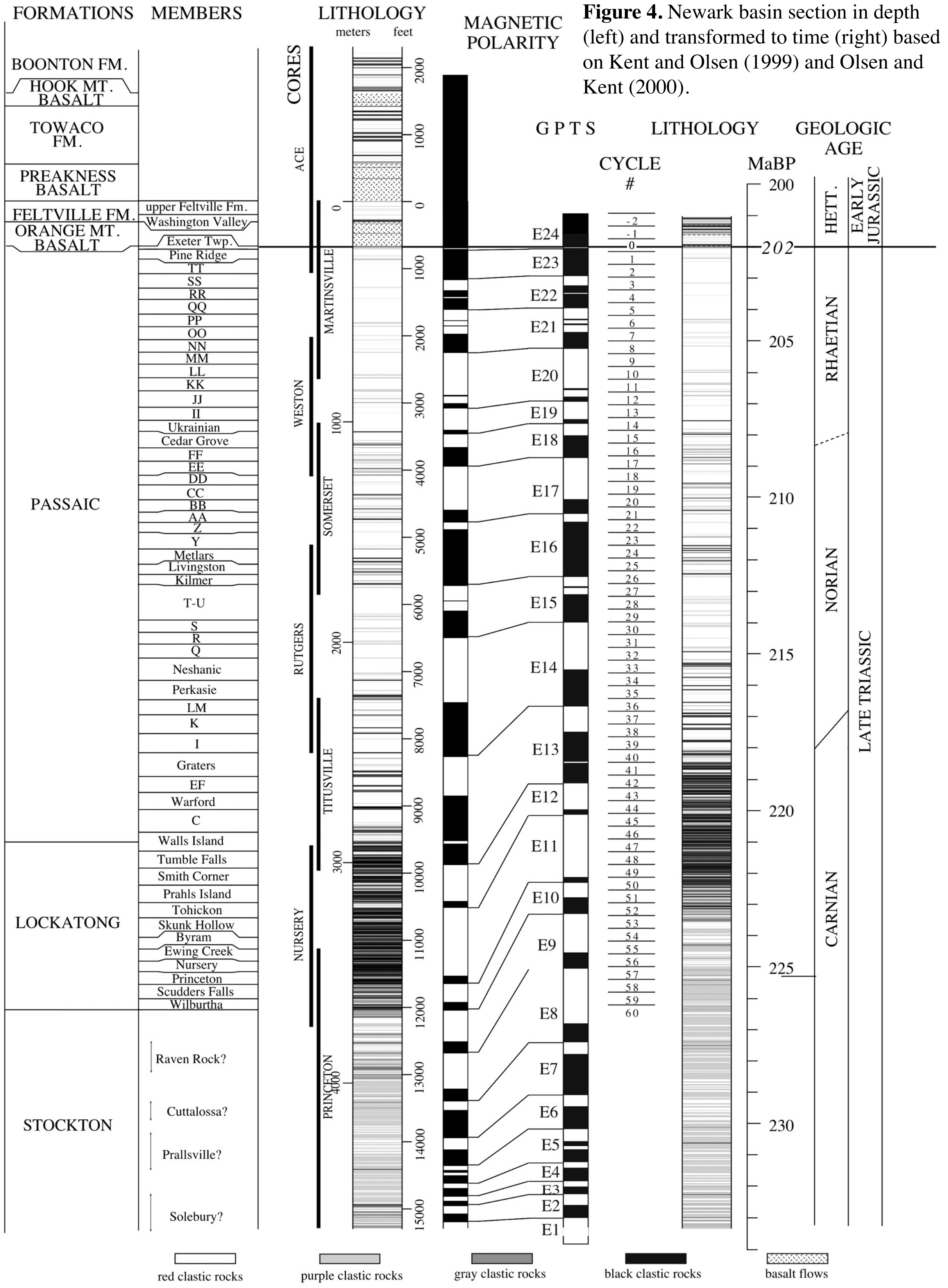


Figure 4. Newark basin section in depth (left) and transformed to time (right) based on Kent and Olsen (1999) and Olsen and Kent (2000).

by nonmammalian synapsids (Shubin and Sues, 1991). The traversodont cynodont synapsids present in these assemblages indicate very close faunal ties to the Gondwanan realm, specifically South America and southern Africa. With the possible exception of the phytosaurs and some stagonolepids, the tetrapod fauna from these paleoequatorial basins actually show little similarity to the classic assemblages from the Late Triassic Chinle and Dockum formations of the western United States or even to the more northerly parts of the Newark Supergroup.

For the Tomahawk assemblage, Sues and Olsen (1990) originally reasoned that because the assemblage appears slightly older than other well-known Laurasian Late Triassic assemblages, and has close affinities to Gondwanan faunules, the differences between the Carnian assemblages of Laurasia and Gondwana were not caused exclusively by geographic isolation. Rather, the differences were an artifact of poor stratigraphic sampling of the Middle Triassic to Late Triassic transition in Laurasia. Thus, differences in age accounted for the lack of similarity among Laurasian assemblages, essentially falling back to the biostratigraphic scheme of Romer (1966).

As outlined below, the new assemblages from Genlee and New Hill may falsify this hypothesis by showing that assemblages with abundant synapsids occur in strata spanning a considerable amount of time, fully overlapping the classic Chinle Group, other Newarkian, and Germanic assemblages, in which synapsids are rare or absent. Again, however, falsification of the hypothesis relying on age differences with classic Late Triassic assemblages must rely on testing the proposed age relationships within the Newark paleoequatorial basins by means independent of the biostratigraphy itself, such as magnetic stratigraphy.

Potentially, the Newark paleoequatorial basins indicate a distinct, temporally-persistent faunal province in which synapsids remained common from at least the mid- Carnian into the Norian - including the youngest paleoequatorial faunas. As is fairly clear from the lithologies involved, these paleoequatorial basins were distinctly humid, with significant coals and no demonstrably coeval evaporites present. This is a very different view from the dry equatorial zone and cosmopolitan faunas envisioned in the currently prevalent models for the Late Triassic (e.g. Shubin and Sues, 1991; Zeigler et al., 1993).

Biostratigraphic Patterns: The associations of taxa seen in the Genlee and New Hill assemblages are new, creating something of a biostratigraphic paradox. For example, both *Aetosaurus* (*Stegomus*) and a dicynodont (cf. *Placerias*) are present in the Genlee and New Hill assemblages. However, most authors have argued that *Aetosaurus* indicates a Norian age (Huber et al., 1993a, b; Lucas et al., 1998; Heckert and Lucas, 1999; Lucas and Huber, 2000), while arguing on the other hand that dicynodont synapsids are unknown from Norian and younger aged strata (Lucas and Hunt, 1993; Lucas, 1998). The new data demand minimally either an extension of the range of dicynodonts into the Norian or an extension of the range of *Aetosaurus* (*Stegomus*). The problem can not by resolved by regarding all the assemblages as being the same age - at least one range extension is required. In addition, it could be argued that the very abundance of synapsids suggests a Middle Triassic age following Romer (1966). Biostratigraphy provides no easy solution to this correlation problem and independent means of correlation are required..

If we use lithological similarity as a correlation tool and the presumed position of possible sequence boundaries (e. g. Olsen, 1997), as well as available palynological and fish data, we can arrive at the correlation of the paleoequatorial faunules seen in Figure 5, which is essentially that of Olsen and Huber (in Clarke, 1997). We recognize that this correlation is not unassailable (e. g. Huber and Lucas, 1993a). However, it does serve as a useful hypothesis to be tested by cyclo- and magneto-stratigraphy, as we have already done in the upper three quarters of the Dan River basin section and the Taylorsville, Newark, and Fundy basins.

High-Resolution Chronostratigraphy Applied to Late Triassic Tetrapod Distribution

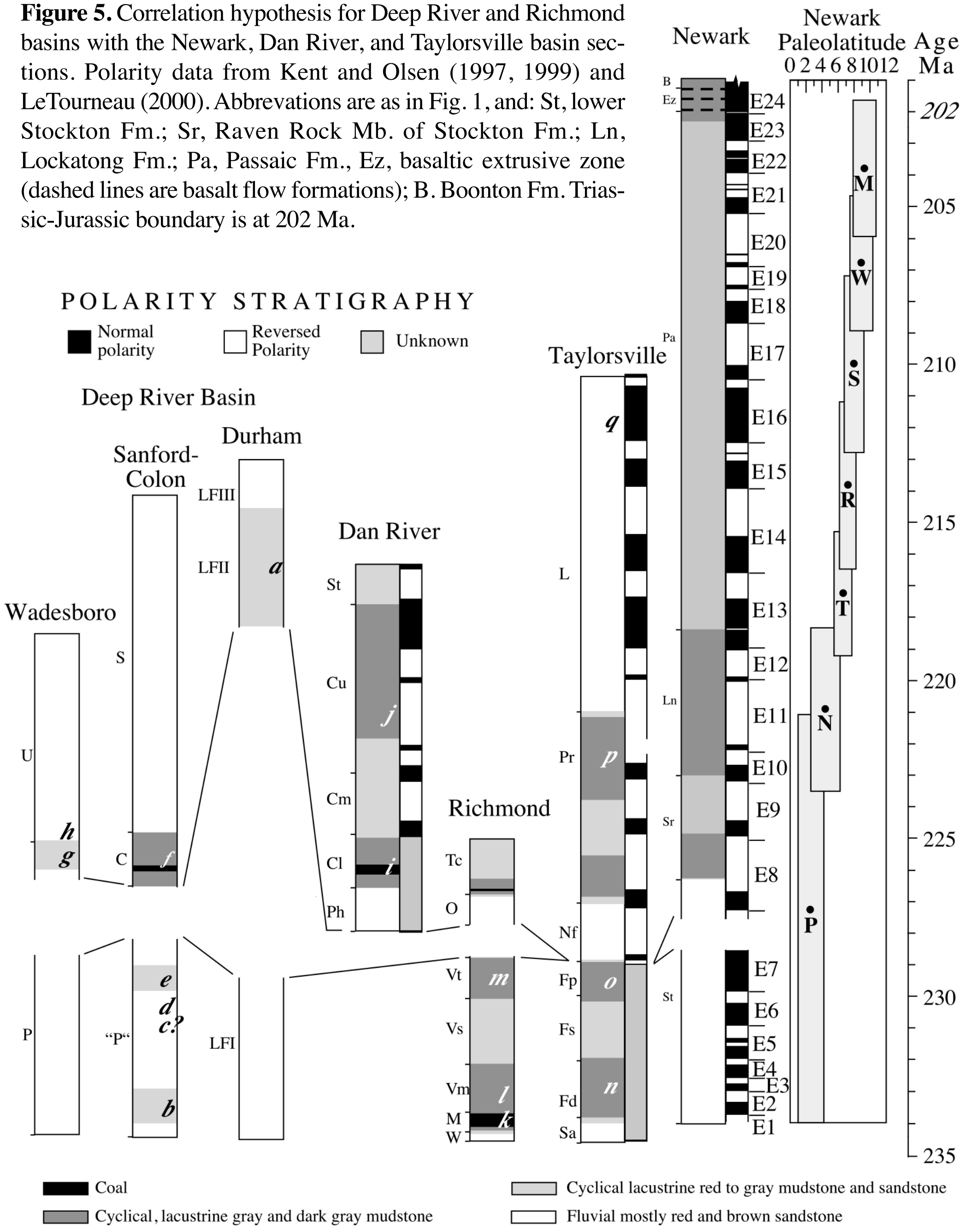
To recapitulate, the problem we want to address is putting this new series of rich tetrapod assemblages from the equatorial Late Triassic in a chronostratigraphic framework that allows biogeographic and biostratigraphic patterns to be evaluated independently. As outlined here and described in our previous publications, we have been able to show that a combined cyclo- and magnetostratigraphic approach can provide an independent, cross-tested, high-resolution temporal framework. There are two separate aspects to this process. First, relative ages can be assessed by physical (superposition) and magnetostratigraphic correlation to the each other and the Newark basin geomagnetic polarity sequence. Second, in the absence of radiometrically datable rocks, numerical ages of the assemblages and the duration between assemblages can nevertheless be precisely estimated by correlation to the Newark basin astronomically tuned time scale by magnetostratigraphic means, and by independent estimates from the cyclostratigraphy of the paleoequatorial sequences themselves.

Newark Basin Time Scale: Previous NSF-funded scientific coring in the Newark basin has resulted in an astronomically-tuned geomagnetic polarity time scale for the Late Triassic and earliest Jurassic that will be our main chronostratigraphic framework and target for correlation of the sections containing the new tetrapod assemblages (Fig. 4 & 5) (Kent et al., 1995; 1999, 2000a; Olsen and Kent, 1999). Using the hierarchy of astronomically-forced lake level cycles that permeate the upper three quarters of the Newark basin record, we have been able place most of the 60 magnetic polarity zones documented in the Newark basin into a temporal framework with a nominal 20,000 year level of resolution (Olsen, 1986; Olsen and Kent, 1996). It is this time scale that allows high-resolution correlation with other basins, as we have done in upper portions of the Dan River (Kent and Olsen, 1997), Taylorsville (LeTourneau, 1999), and Fundy (Kent and Olsen, 2000b) basins (Fig. 5). However, strata older than the Raven Rock Member of the Stockton Formation lack obvious cyclicity. This is unfortunate, because there are some indications that the oldest parts of the Newark basin section might be Middle Triassic in age (Ediger, 1986; Olsen et al., 1989; Olsen, 1997), which could provide links to developing pre-Late Triassic cyclo- and magneto-stratigraphies and radiometrically dated sequences elsewhere (e. g. Muttoni et. al., 1998; Hinnov and Park, 1998)

Paleogeography and Paleoclimate

Paleomagnetics provide the only direct information on paleolatitudes, and are therefore essential in assessing the paleogeographic and paleoclimatic context of the new tetrapod assemblages. The presence of coals and associated black shales, and lack of evaporites, suggests a humid, tropical setting for the Newark Supergroup basins of the southeastern US. Until recently, however, it was assumed that these indicators of humid paleoclimate were coeval with more arid facies at the same latitudes at about 15° N, suggesting that non-zonal climatic processes were responsible for those apparently conflicting climatic indicators (Manspeizer, 1982). This interpretation was also partly responsible for the widely held perception that the early Mesozoic was a time in which a humid equatorial zone was essentially lacking (Zeigler et al., 1993; Wilson, et al., 1994). Our paleomagnetic work in the Newark basin and concordant paleomagnetic data from the Dan River and Fundy basins show that there was significant northward drift of the Newark Supergroup basins during the Early Mesozoic (Kent et al., 1995, 1997), and that this drift coupled with poor temporal resolution was responsible for the apparently conflicting paleoclimate indicators. In fact, reanalysis of the paleoclimatic indicators within the much better constrained more recent paleomagnetic framework indicates that not only was there an equatorial humid belt, but that the tropical climatic gradients were very similar to those of today (Kent and Olsen, 2000b).

Figure 5. Correlation hypothesis for Deep River and Richmond basins with the Newark, Dan River, and Taylorsville basin sections. Polarity data from Kent and Olsen (1997, 1999) and LeTourneau (2000). Abbrevations are as in Fig. 1, and: St, lower Stockton Fm.; Sr, Raven Rock Mb. of Stockton Fm.; Ln, Lockatong Fm.; Pa, Passaic Fm., Ez, basaltic extrusive zone (dashed lines are basalt flow formations); B. Boonton Fm. Triassic-Jurassic boundary is at 202 Ma.



However, there are as yet no paleomagnetic data from the coal-bearing sections themselves, most notably in the Deep River and Richmond basins. Whilst we believe that our paleogeographic inferences are robust, they are based on the Newark basin spaciotemporal framework assuming the untested temporal correlation in Fig. 5. Obviously direct paleolatitudinal data from paleomagnetics are needed from these sequences, in order to test these assumptions and the climatic pattern deduced from them.

PROPOSED WORK

In order to make geographic and temporal sense out of the new paleoequatorial faunal assemblages and the associated paleoenvironmental information, we propose to test the correlation outlined in Fig. 5 by a concerted effort at working out their magneto- and cyclostratigraphy, building on our results in more northern basins (i.e., Newark - Fig. 4) and the completed portions of the Dan River and Taylorsville basins (Fig. 5).

The goals of this project require that we outline the physical, magnetic, and cycle stratigraphies of substantial parts of the sections of the Durham, Sanford, and Wadesboro subbasins of the Deep River basin, and lesser amounts of the Dan River, Richmond, and Taylorsville basins. Our specific plans are outlined below.

1) Lithostratigraphy: We plan to examine and log suitable industry and scientific drill holes and cores for their basic lithostratigraphy, paying special attention to attributes that have paleoclimatic significance (e.g. coals, black shales, caliche, evaporites). This will be especially significant in the Sanford and Durham subbasins of the Deep River basin, and the Richmond basin where there are hundreds of meters of core and many thousands of meters of cuttings in hand (NC and VA geological surveys). One of us (PML) has already completed this for most of the available material in the Richmond and Taylorsville basins (LeTourneau, 1999).

Quarries and a few major stream cuts will provide the basis for lithostratigraphy in the rest of the basins. We have had great success working in natural stream outcrops in the southestern US, where we routinely observed 25% to 75% fresh outcrop in the bottom of streams suitable for magnetostratigraphy (Kent and Olsen, 1997). Specific quarries that cover significant section are already identified in both the Deep River and Dan River basins as well; some of these are the same quarries that have produced the new faunas.

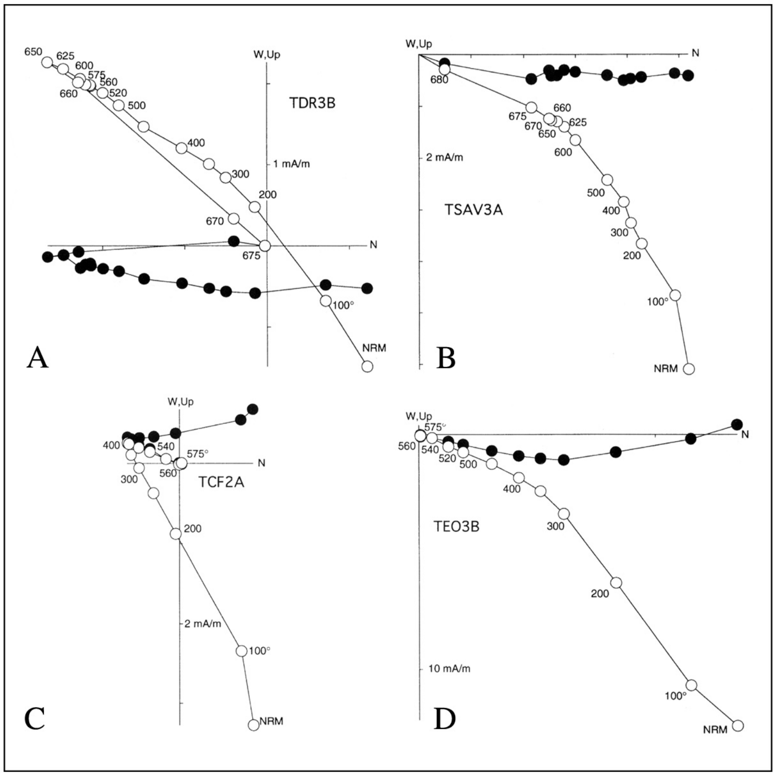


Figure 6. Vector end-point demagnetization diagrams of natural remanent magnetization of representative samples from upper member of the Cow Branch Formation of the Dan River basin sections. The open and closed symbols are plotted on vertical and horizontal axes, respectively, in geographic coordinates. Thermal demagnetization levels (in degrees Celsius) in all diagrams Samples are: **A** and **B,** red mudstones with recent and ancient overprints, as well as normal (A) and reverse (B) polarity; and **C** and **D**, gray mudstones with a recent overprint and reverse (C) and normal (D) polarity. Modified from Kent and Olsen (1997).

2) Magnetostratigraphy and Paleolatitudes: The most-diagnostic sections that can be studied with the highest probability of success are: 1) lower member of the Cow Branch Formation of the Dan River basin; 2) Cumnock Formation of the Sanford subbasin; and 3) upper type Pekin Formation of the Wadesboro basin. We already know from reconnaissance and published data that at least the upper type Pekin Formation and the Cow Branch Formation (Kent and Olsen, 1997) have recoverable ancient magnetizations suitable for magnetostratigraphic and paleolatitude determinations (Fig. 5). The target outcrops and exposures have already been identified and large amounts of core from the Pekin, Cumnock, and Sanford formations are available at the North Carolina Geological Survey (Raleigh). The paleomagnetic stratigraphies in each of these three sections, compared both to each other and to the correlative parts of the Newark basin time scale, will allow multiple tests of the coherence of the cyclostratigraphy and magnetostratigraphy.

The Dan River basin study (Kent and Olsen, 1997) serves as a useful model for an effective sampling and analytical strategy with outcrop in a southern Newark Supergroup basin. We sampled 3000 m of section with 113 sites. This is a practical sampling density of about 25 m per site. The sampled part of the Dan River section has an estimated sedimentation rate of around 500 m/myr, corresponding to a nominal temporal resolution of about 50 Kyr. Assuming similar facies in the lower part of the Dan River basin section and the Deep River basin section, a similar sampling density should be adequate to delineate the polarity stratigraphy, because the mean duration of polarity intervals based on the Newark geomagnetic polarity time scale is expected to be around 500 kyr (with the large variability typical of the inherently stochastic reversal process; Kent and Olsen, 1999). Available core provides an opportunity for much closer sampling to check on the magnetic polarity determinations.

We estimate that a total of ~5500 m of measured section will be analyzed for this study. One of the thickest sections is in the Sanford subbasin and Colon cross-structure, which contain an estimated 2500 m of section in outcrop, with approximately 1000 m of core housed at the NC Geological Survey. The Wadesboro subbbasin contains a thick section, but we plan on sampling only a modest section of about 200 m in its cyclical portion; and there is at least 1000 m of section that can be sampled in the Durham subbasin of the Deep River basin. These sections should collectively provide excellent stratigraphic coverage and control for the Deep River basin, which contains many of the important fossil assemblages.

The Taylorsville and Richmond basins potentially provide a cyclostratigraphy for the oldest part of the section as well as ties to critical tetrapod assemblages, but we plan on concentrating (at least initially) on the parts of the section known to have red intervals, comprising a few hundred meters of section. Study of the ~500 m of the Cow Branch Formation in the lower part of the Dan River basin section would extend the well-characterized magnetostratigraphy of the middle and upper parts of the Dan River basin (Kent and Olsen, 1997) to some of the most cyclical parts of the section.

We will use standard paleomagnetic laboratory and analytical techniques that we successfully employed in our previous studies of Newark Supergroup rocks. These include: 1) *complete progressive thermal demagnetization* to identify secondary and characteristic magnetizations; 2) *principal component analysis* to determine their directions; 3) *fold and reversal tests* wherever possible to constrain the age and fidelity of the magnetizations; and 5) *rock magnetic experiments* such as IRM acquisition and thermal demagnetization to better understand the origin and reliability of the paleomagnetic record. The magnetic stratigraphy will be integrated with the cycle stratigraphy both to convert thickness to time and for correlation. The paleolatitudes determined from the magnetic inclinations will be used to assess the paleoclimatic significance of the lithofacies.

3) Cyclostratigraphy: All of the tetrapod assemblages here except that from Genlee, NC, come from strata ostensibly older than the Lockatong Formation, based on our straw-man correlation (Fig. 5). Fortunately, many of the fine-grained intervals of the Newark Supergroup paleoequatorial basins have well developed cyclicity (Fig. 1). A combined cyclo- and magneto-stratigraphic approach in these basins should allow astronomical calibration of the portions of the Newark basin time scale where that has not been heretofore possible.

Published studies indicate that the Cumnock Formation of the Sanford subbasin (Hu and Textoris, 1994), the middle shale of the Wadesboro subbasin (Olsen et al., 1991), and the lower member of the Cow Branch Formation of the Dan River basin are fine grained and exhibit well developed cyclicity (Fig. 1). The Falling Creek Formation of the Taylorsville basin and the Vinita Formation of the Richmond basin (Ediger, 1986) are also cyclical. We plan to use the observational and analytical tools we developed for the Newark basin (Olsen, 1986; Olsen et al., 1997; Olsen and Kent, 1999) in these paleoequatorial basins, concentrating on the best cores, geophysical logs of holes, and quarry exposures, and most of all, stream-bed outcrops. When tied by magnetostratigraphy to the Newark basin time scale (Fig. 4), this cyclicity should allow us to extend astronomical calibration to the older parts of the Carnian and perhaps even strata of latest Middle Triassic age. In addition, cross-correlation within coeval sections of different paleoequatorial Newark basins will allow internal tests of the coherency of the paleomagnetics and cyclostratigraphic calibration.

Work Plan

Year 1: Main phase of fieldwork in basins. Initial paleomagnetic and cyclostratigraphic analysis. Presentation of initial results at AGU.

Year 2: Follow up field work, completion of paleomagnetic and cyclostratigraphic analysis. Presentation of main results at AGU and writing up of papers.

RELATION TO OTHER WORK

We have two ongoing NSF projects that relate to the current proposal. One, "Filling the Norian (Late Triassic) Gap in Tropical Tetrapod Diversity, Eastern North America" (EAR 98-14475 to P. E. Olsen and H.-D. Sues) focuses on the discovery and phylogenetic analysis of new faunal remains from the Late Triassic, largely from the more northern Newark Supergroup basins, but it also has been responsible for much of the paleontological work done on the southern basin assemblages, and, in fact, provided the motivation for this proposal. This proposal, on the other hand, focuses on the paleogeographic and chronostratigraphic context for our discoveries from the previous grant. The other project is "Testing the J1 Cusp and Supposed Association with Normal Polarity Massive Flood Basalts in the Hartford Basin" (beginning July, 2000; D. V. Kent and P. E. Olsen). While this project should add significantly to our overall understanding of the time scale of the early Mesozoic and the Newark Supergroup in general, it deals exclusively with Early Jurassic age strata of the Hartford basin of Connecticut and Massachusetts; although the study compliments the current proposal, there is no direct overlap.

Collaboration with the North Carolina Museum of Natural Sciences: Vince Schneider, Curator of Paleontology at the North Carolina Museum of Natural Sciences in Raleigh, NC will be coordinating three members of his staff who will be working with at no cost to this proposal. He and his three staff members will assist us in field work as well as collection of any new fossil material we may find.

BROADER IMPACTS

Biogeography and Biodiversity: This proposal seeks funds to place critical faunas from uniquely paleoequatorial basins of Late Triassic Pangea in a well constrained temporal and geographic context. This is necessary to understand the meaning of the apparent unique aspects of those faunas. The apparent temporal persistence of biogeographic provincialism in the face of a lack of obvious geographic barriers is a conundrum that is at the heart of understanding what makes ecosystems coherent entities. In turn, knowledge of the Late Triassic pattern of faunal and floral provinciality is vital to an understanding of the massive biotic reorganization that was a consequence of the Triassic-Jurassic mass extinction, which was one largest of the five largest mass extinctions in the Phanerozoic. Indeed, the apparent homogenization of the global continental biota and pattern of recovery after that mass extinction cannot be understood without the background of Late Triassic provinciality, which can ultimately provide critical context to the present-day biodiversity crisis and its ultimate ramifications.

Origin of Major Groups: This project also has the potential to put into temporal perspective the phylogenetic relationships of stem and sister taxa of major groups such as synapsids, lepidosaurs, crocodylomorphs, and dinosaurs. For example, *Microconodon* from the Deep River and Richmond basins, and *Adelobasileus*, the putative earliest mammal from the Chinle Group (Lucas and Luo, 1993), are almost certainly very closely related to each other if not synonymous, and are likely the sister group of the Mammaliformes (sensu Rowe, 1988 and Luo, 1994). Similarly, the new sphenosuchian from the Genlee assemblage may be among the oldest in this group (depending on how its assemblage correlates with the Newark basin time scale), and hence is likely to be critical in the origin of the Crocodylomorpha. The admittedly very scrappy ornithischian dinosaur remains likewise may very well be the oldest, or certainly among the oldest, dinosaurs known.

Astronomical Forcing: Although not emphasized in this proposal, the correlation and cyclostratigraphy of the southern basins will provide important new information of the overall Pangean climatic response to orbital forcing. Not only does this information help us understand climate processes in the hot house Pangean world of the Early Mesozoic, but it also gives us a template for understanding the basic effects of orbital forcing of modern tropical continental climate.

Educational Benefit: Finally, this projects enhances general knowledge of the paleontological heritage of the southeastern United States, an area hitherto not known for superb vertebrate assemblages such as these. We will coordinate fieldwork and provide the North Carolina Museum of Natural Sciences (Raleigh, NC) and the Virginia Museum of Natural Sciences (Martinsville, VA) with the results of our work, as well as any significant fossil material we may find. We anticipate that the results of this work will be incorporated into their educational outreach programs, as it has been in the past, and thus be integrated into the educational systems of North Carolina and Virginia. In addition, we will be constructing a web site designed to disseminate the results of our work to both a technical and lay audience, as we have done with other recent NSF-funded projects (see prior results).