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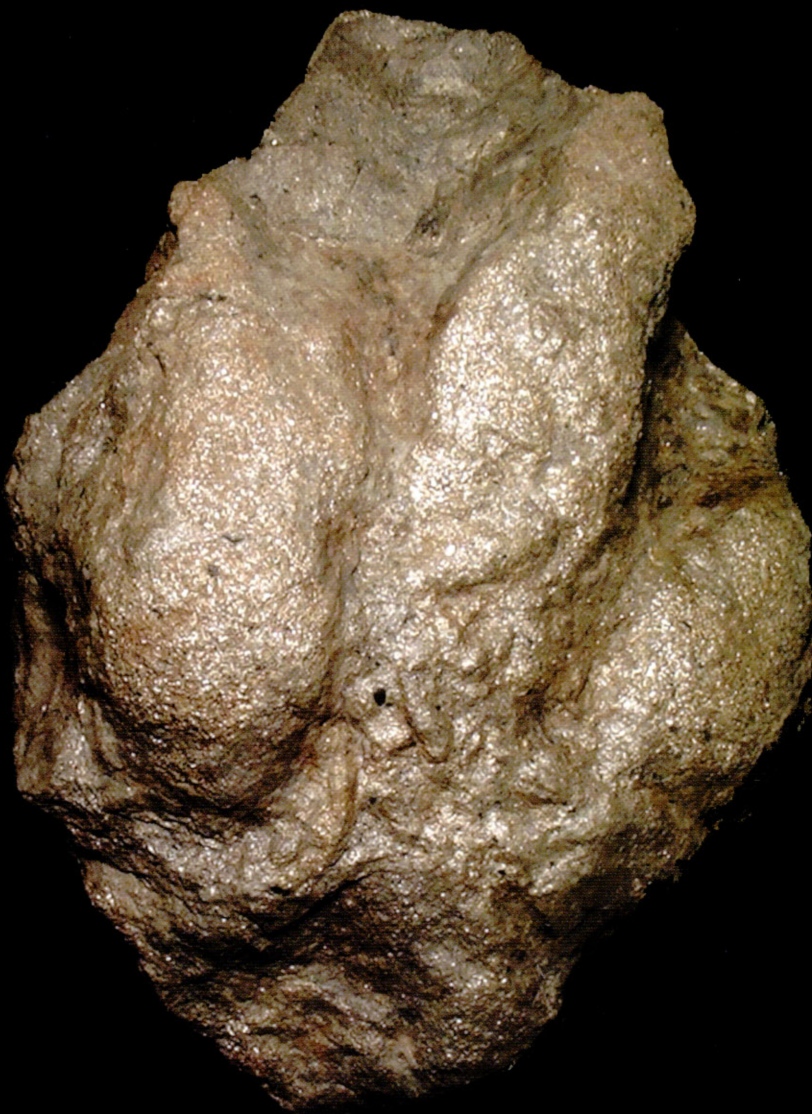

Cover Story

The "Age of Dinosaurs" in the Newark Basin

By Paul E. Olsen, and Emma C. Rainforth

The modern Connecticut and Hudson rivers flow through valleys with an ancient history. These valleys formed as part of a remarkable series of tectonic "rift basins" during the early part of the Mesozoic era, more than 230 million years ago. These basins formed during the fragmentation of the supercontinent of Pangea. The Newark Basin of southeastern New York, eastern and central New Jersey, and south eastern Pennsylvania is a part of this rift system. It is one of the largest segments of these rifts exposed in North America, and the sediments filling all of these rift valleys are collectively called the Newark Supergroup. The rocks of the Newark Supergroup offer an amazing window into the early part of the age of dinosaurs, and to the mass extinction event that set the dinosaurs on their course to dominate the world during the remainder of the Mesozoic.

Continental rifting seems to have begun in eastern North America sometime in the middle of the Permian Period (260 million years ago) and finished in the Early Jurassic (190 million years ago). These rifts - in particular the Newark basin - also record a major tectonic paroxysm that punctuated the beginning of the Jurassic: the formation of huge of intrusions and extrusions of basaltic magma, known as the Central Atlantic Magmatic Province, or CAMP.

The climate during this during the Triassic and Early Jurassic was remarkably equable, with no ice at the poles – sometimes referred to as a "Hot House" mode. During this time, Pangea straddled the equator, drifting slowly northward through time. As a consequence, the Newark basin itself slowly drifted from the wet tropics towards the arid climate belt, producing a transition that is well displayed in the basin sediments.

As is true for tropical climates today, the climate of the Triassic and Early Jurassic fluctuated dramatically in precipitation, following cycles driven by variations in the Earth's orbit. These cycles are recorded by changes in the levels of lakes in Newark Supergroup rocks. In addition to providing a constantly fluctuating sedimentary environment, these cycles provide a stratigraphic framework for the basins and a mechanism by which to calibrate the Late Triassic-Early Jurassic time scale.

Biologically, the Triassic and Early Jurassic witnessed profound changes. The early Mesozoic followed the largest mass extinction of all, at the end of the Permian. Yet land-living vertebrates, or tetrapods, of the Early Triassic largely continued the Paleozoic-style dominance of the oxymoronically-named "mammal-like reptiles" (more properly called "synapsids"). Throughout the Triassic, however, other reptilian groups, including lizards, crocodilians, and dinosaurs and their relatives became progressively more abundant, diverse, and larger, so that by the beginning of the Late Triassic synapsids were relatively rare. By the early Late Triassic dinosaurs had evolved, but they did not become truly dominant until after the next great mass extinction at the Triassic-Jurassic boundary. This great transition to dinosaurian dominance is recorded in detail in Newark Supergroup and particularly Newark basin deposits.

Stratigraphic Context

As a result of over a century of intensive geological research, the Newark Supergroup is known in more stratigraphic detail than any other central Atlantic margin rift, and arguably any rift of any age. Virtually the entire stratigraphic section of the Newark basin was cored by the US National Science Foundation-funded Newark Basin Coring Project. Based on all of this work, the rocks of the Newark Supergroup can be divided into four several distinct sequences that formed under particular tectonic conditions. Three of these four (sequences II, III, and IV) can be seen in the Newark Basin: sequence II is of Middle Triassic to early Late Triassic age, sequence III is of early Late Triassic age; sequence IV is of latest Triassic to Early Jurassic age, and contains the Triassic-Jurassic boundary, and the extensive basalts of the CAMP. These sequences do not correspond perfectly to the traditional formational boundaries in the Newark and other east coast basins.

These three sequences were probably initiated by major pulses of regional crustal extension. This extension deepened the rift basins, making room for sediments to accumulate. The basin depositional environments thus generally follow a three-fold history, consisting of riverine sediments, succeeded by sediments that accumulated in rapidly-deepening lakes, finally followed by slow shallowing, all caused by the consequence of growth in area of the rift as extension proceeded. The slowing or cessation of the tectonic extension would cause additional shallowing and thus a return to riverine deposition. Each new pulse of extension would be accompanied by erosion of the valley walls, creating new sediments and rocks.

One of most dramatic features of the Newark basin sedimentary record is its pervasive cyclicity. This cyclicity was caused by changes in the Earth's rotation, cycles that occur on periodicities of around 20,000, 100,000, and 400,000 years (and perhaps also even longer cycles of 1.75 and 3.5 million years). As the Earth's relationship to the sun changes with each cycle, this alters patterns of precipitation, which alters erosion and deposition of sediments, creating different sediments, most obviously in the sediments of giant lakes.

Tectonic History

It is becoming increasingly clear that the latest Paleozoic and Mesozoic tectonic history of eastern North America, including the Newark basin, is much more complicated than is usually thought of for what is usually called a "passive margin".

Continental breakup may have begun as early as the Permian, more than 250 million years ago, but spreading did not begin in earnest until the Middle Triassic, marked by the formation of many relatively small basins that filled with sequence II strata. At about 227 million years ago, a larger pulse of extension, marked by a hiatus between sequences II and III, coalesced and enlarged many of these smaller basins. This was followed by the last known major pulse of extension at about ~201 million years ago, which resulted in the emplacement of the intrusives and extrusives of the CAMP, and the deposition of the sediments of sequence IV.

In the Newark basin, sequence III is by far the most widespread and, at least in outcrop, the most heterogeneous portion of the basin fill. This sequence is includes parts of the Stockton, all of the Lockatong, and part of the Passaic formations. This sequence is characterized by the dominance of cyclical lake- and river-deposited strata. It is richly fossiliferous, especially in the northeastern part of the basin.

The Lockatong Formation consists almost entirely of dramatically cyclical mudstone, and these rocks are the most fossiliferous in the Newark basin section. The full suite of lithological cycles attributed to astronomical forcing is present. In general, the most fossiliferous cycles tend to be those in the wettest phases of the cycles. Plant fossils assemblages are surprising rare in these rocks, but animal remains can be exceedingly common. Invertebrates found so far include: several types of clams, trace fossils , and crustaceans. Vertebrate body fossils are dominated by an assemblage of aquatic and lake margin forms, including abundant and fairly diverse articulated fish and small reptiles as well as and phytosaur teeth; tetrapod footprints can be very abundant, and include one spectacularly well-preserved assemblage. Vertebrate coprolites are common in many layers.

In the northeastern Newark basin, on both sides of the Palisade sill – which is the remains of a giant flow of basaltic magma, the outcrop belt along the Hudson River is remarkably rich in vertebrate fossils, despite varying degrees of metamorphism.

A notable feature of the finely laminated rocks near the Hudson River is the truly remarkable abundance of fish, especially the coelacanth *Osteopleurus*, the palaeoniscoid *Turseodus*, and the holostean *Semionotus* (Figure 1). Less common in the same units is a large coelacanth, probably *Pariostegeus* sp., the palaeonisciform fish *Synorichthyes* and *Cionichthyes*, the gliding lizard-like lepidosauromorph diapsid *Icarosaurus seifkeri*, and phytosaur teeth. More massive mudstones usually have scraps and sometimes more complete remains, including a skull, of phytosaurs; metoposaur amphibian fragments; and locally-common fish fragments and coprolites. Only a few poorly preserved reptile tracks, all small probable-dinosaurian forms, have been found.

Passing further to the north along the Hudson into Rockland County, the Newark sediments consist of alternations of sequences of mostly red sandstones with minor purple and tan sandstones and red mudstones, and similar-scale sequences of purple, gray, and tan sandstones and conglomerates with subordinate red and purple mudstones. Fluvial, deltaic and marginal lacustrine facies appear to be present. We presume that the more red sequences represent drier phases of the climate cycles, but cannot demonstrate this.

Both types of sequences contain abundant fossils, including bones. Fossil bones found so far include phytosaur teeth and bone scraps, a small amphibian dermal bone, an unprepared portion of a possibly reptilian skull, and numerous indeterminate bone fragments. Reptile tracks include poorly preserved trackways from Blauvelt, New York, which have been widely assigned to the small ceratosaurian theropod dinosaur *Coelophysis* (Figure 2). However this designation is probably incorrect, and in fact the tracks more likely belong to *Atreipus* , which was most likely made by an ornithischian dinosaur. *Atreipus* tracks have also been reported from Grandview, New York and several localities in the Lockatong formation in Pennsylvania. However, smaller tracks (called *Grallator*) probably made by a small theropod dinosaur very similar to *Coelophysis* have been found in Upper Nyack, New York, although there is no other evidence of *Coelophysis* itself from eastern North America. *Grallator* tracks have been found elsewhere in the Lockatong Formation of the Newark basins, and they become more common in the succeeding formations.

As we move upward in the stratigraphic section, the apparent wetness of the climate decreases cyclically. Part of this trend is certainly due to the northward drift of Pangea, carrying the Newark basin into more arid climes, as evidenced by the increase in evaporates. However, this trend is also due in part to the progressive filling and widening of the basin through the waning phases of the major extensional pulse responsible for the formation of sequence III.

Tetrapod remains are the most spectacular fossils from the Passaic Formation. Diverse and often very well preserved tetrapod footprints are very abundant at many horizons. The richest areas are the northeastern and southwestern parts of the basin. The abundance and size of theropod dinosaurian tracks, traditionally placed in the ichnogenera *Grallator* and *Anchisauripus*, increase through the Passaic.

Discoveries of reptile bone are becoming increasingly common in these rocks. In particular, red and gray massive root-bearing sandstones and siltstones contain abundant remains, including several groups of amphibians and reptiles. One locality has produced several hundred specimens of the procolophonid reptile Hypsognathus, including five skulls and three partial skeletons.

The boundary between sequences III and IV occurs well below the Triassic-Jurassic boundary as defined on fossil pollen (the international standard). There is no evidence for — and much against — an unconformity or hiatus at the Triassic-Jurassic boundary in the Newark basin.

Sequence IV rocks contain a host of fossil plants. Invertebrates preserved in these rocks include various trace fossils, crustaceans, and insects. All of these occur in gray thin-bedded, although not finely laminated, silty claystones and limestones.

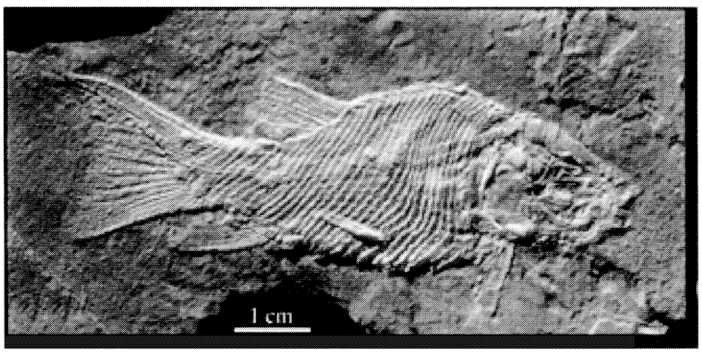

Figure 1 *: The holostean fish* Semionotus braunii, *Yale Weehawken quarry, NJ.*

Articulated and often beautifully-preserved fish are abundant in finely laminated beds in the Feltville, Towaco, and Boonton Formations. These include the large coelacanth *Diplurus longicaudatus*, the palaeonisciforms *Ptycholepis marshi* and *Ptycholepis* sp., the palaeonisciform *Redfieldius* spp., and the holostean *Semionotus* spp. (Figure 1) The *Semionotus* are extremely diverse; their "species flocks" have been compared to those seen in modern cichlid fishes in the Great Lakes of East Africa. Some of the fish from sequence IV are among the best preserved early Mesozoic fish from anywhere in the world.

Tetrapod footprints are more common in sequence IV sedimentary units than in any other part of the Newark basin section, with a few localities having produced tens of thousands of specimens. Three footprint assemblage types occur within sequence IV. The oldest is restricted to sequence IV strata below the Triassic-Jurassic boundary, and is indistinguishable from older Triassic assemblages in the basin. *Rhynchosauroides* sp., *Gwyneddichnium* sp., *Apatopus* sp., *Brachychirotherium parvum*, *Batrachopus cf. B. bellus*, and *Batrachopus deweyii* occur, along with abundant specimens of the theropod dinosaurian forms *Grallator* spp. and *Anchisauripus* spp.

The second type of assemblage occurs directly above the Triassic-Jurassic boundary and consists entirely of *Rhynchosauroides* n. sp., *Batrachopus deweyii, Grallator* spp., *Anchisauripus* spp., and for the first time, the large theropod track *Eubrontes giganteus*. All the forms typical of the Triassic are absent, even though this is one of the most heavily-sampled levels within the Newark basin.

The third type of assemblage occurs in the Feltville, Towaco, and Boonton Formations. This assemblage is similar to that from just above the Triassic-Jurassic boundary, but the ornithischian dinosaur *ichnite Anomoepus scambus* is present at most localities, the mammal-like synapsid track *Ameghinichnus* n. sp. occurs at one locality, and *Rhynchosauroides* sp. is restricted to a single specimen from the same approximate level as *Ameghinichnus*. The tetrapod footprint assemblages thus follow the turnover pattern seen in the fossil plant assemblages.

In contrast to the exceedingly abundant and well-preserved tetrapod footprint assemblages, fossil bones from the Jurassic of the Newark Basin are virtually absent. Thus far there are only a few bone flakes in a coprolite, and a shard of a large tooth, probably of a theropod dinosaur, from the natural cast of a *Eubrontes giganteus* footprint!

Biotic Change at the Triassic-Jurassic Boundary

The Newark Supergroup, particularly in the Newark basin, is one of the best venues in the world for examining faunal change across the Triassic-Jurassic boundary. Based on the Newark timescale and paleontological correlations with areas outside the region, a consistent picture emerges of the profound changes that occurred around the boundary, with some indications of what the causal mechanism for these changes may have been.

During the Late Triassic terrestrial tetrapod and plant communities varied in composition in different regions of the globe. We don't know exactly how these distributions changed through time, but some trends are evident. It is clear that to some extent the faunas and floras tracked climate as central and southern Pangea drifted north. It is also apparent that in most areas dinosaurs replaced synapsids and became more abundant, diverse and larger through the Triassic. The Early Jurassic global biota was much less heterogenous. Most floral provinciality was gone. Conifers were extraordinarily dominant in the tropics, a pattern that would continue until the mid-Cretaceous.

Tetrapod communities of Early Jurassic, in contrast, appear to have been virtually cosmopolitan. Prosauropod and large theropod dinosaurs (larger than any in the Triassic) seem to have achieved nearly global distribution, along with crocodiles and several other groups, with the same genera being reported from Arizona, southern Africa, Nova Scotia and China. Diversity seems to have been much lower. There were no longer any synapsid-dominated communities. Large amphibians were completely restricted to higher latitudes and had very low diversity. Most critically, apart from dinosaurs, non-crocodylian archosaurs were essentially gone; these had been the most common large tetrapods of the of the Late Triassic tropics. All in all, roughly 50% of all tetrapod families seem to have become extinct at or near the Triassic-Jurassic boundary, making this mass extinction, at least as far as tetrapods are concerned, even larger that that at the Cretaceous-Tertiary (K-T) boundary.

The rate at which this change occurred can presently be assessed only in the Newark Supergroup, and most of the evidence comes from the Newark basin. In the central Atlantic margin rifts, the floral change was evidently very abrupt, estimated to have

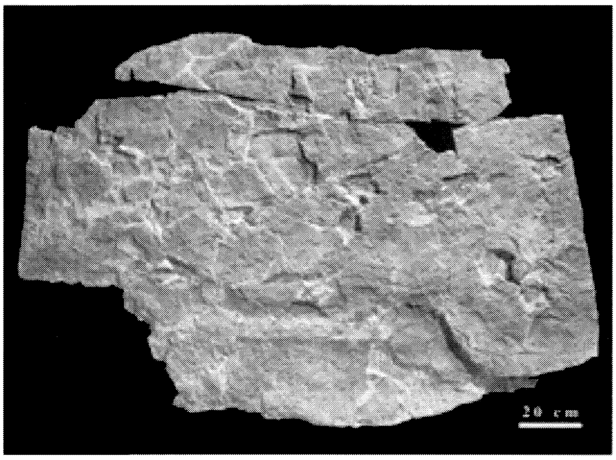

Figure 2: *Indeterminate dinosaur tracks (possibly* Atreipus*) from Blauvelt track locality, now at the New York State Museum, Albany (Blauvelt, New York).*

occurred over less than 20,000 years, and probably actually much less. A similarly abrupt change may well have occurred among tetrapods.

Recent research indicates that in the Newark basin, these profound floral and faunal changes are directly associated with a "fern spike" (a sharp abundance of fern spores) and an iridium anomaly. The floral and faunal pattern (with the exception of the survival of dinosaurs) and the associated iridium anomaly is strikingly similar to the pattern seen at the K-T boundary, which suggests a similar cause for both extinctions – a giant asteroid impact – a suggestion which had repeatedly been made long before the new biotic and Ir data were available.

And then there were the volcanic eruptions. One the most striking aspects of the Triassic-Jurassic boundary in the central Atlantic margin rifts is the direct superposition of the oldest CAMP basalts on the boundary. A possible causal link is therefore difficult to ignore, given a similar (although less precisely timed) coincidence between the similar large igneous flows and other major extinctions (the Deccan Traps of India and the K-T boundary and the Siberian Traps and the Permo-Triassic boundary).

Thus the three largest mass-extinctions of the last 250 million years are evidently very close in time to the three largest flood basalt provinces, and all three have at least some evidence of asteroid impacts. Is volcanism connected to impact? We don't know. A mechanism linking impacts with flood basalts has been proposed, but it is still difficult to reconcile with both observations and modelling. It seems plausible that a massive impact might be able to concentrate a distant flood basalt province that was close to eruption, but more work on this topic is definitely required.

Suggestions for Further Reading

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ON THE COVER:

On the cover: Dinosaur Footprint, Eubrontes sp., *Late Jurassic, Chestnut Brook, Cromwell Ct. PRI Specimen number 41121. Length appx. 25cm. Photo by Phoebe Cohen. In this issue, Paul Olsen and Emma Rainforth summarize the state of our knowledge of this and other extrordinary fossils of the Triassic-Jurassic Newark Supergroup.*