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# PALEONTOLOGY AND PALEOENVIRONMENTS OF EARLY JURASSIC AGE STRATA IN THE WALTER KIDDE DINOSAUR PARK (NEW JERSEY, USA)

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## INTRODUCTION

The Walter Kidde Dinosaur Park of the Essex County Department of Parks and Recreation in Roseland, NJ is famous for the many thousands of dinosaur and other reptile footprints found by mostly amateur paleontologists (Fig. 1). Despite over 25 years of collecting and innumerable visits by professional geologists, there has been little detailed documentation of the rich fossil assemblages from the site. The purpose of this paper is to provide an overview of the Jurassic age fossils from the site, and to place those remains in their environmental and paleoecological context.

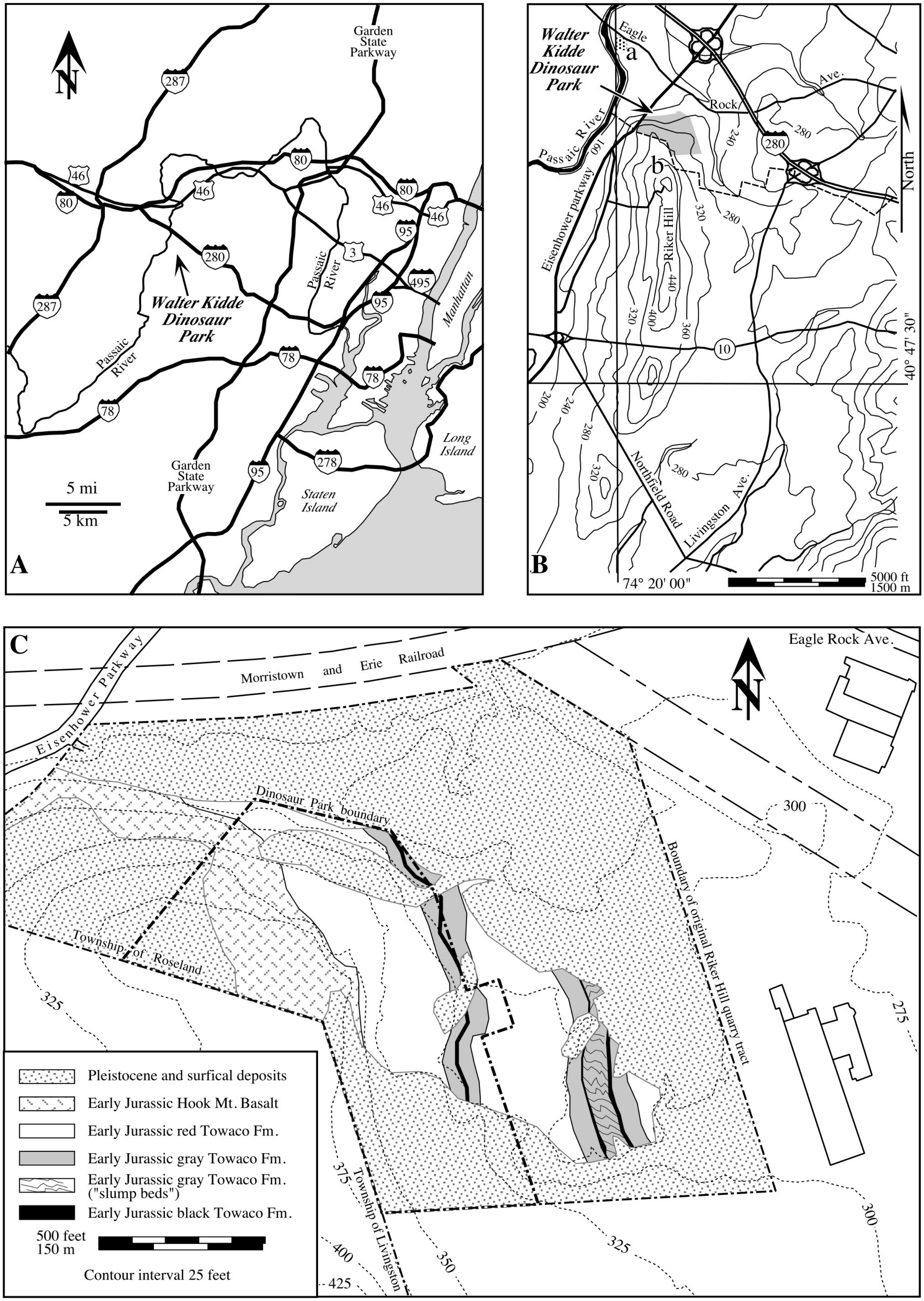
## HISTORY OF COLLECTION

The discovery of dinosaur footprints in the so called "Roseland quarry" or "Riker Hill quarry" (now the Walter Kidde Dinosaur Park) was first reported in the local newspapers of Livingston and Roseland, NJ about 1968. The quarry occupied a 55 acre tract located on the northeast side of Riker Hill in Roseland and was owned by the Walter Kidde Company, Inc. Over the next few years the Riker Hill quarry became locally very well known for its abundant reptile footprints, and in 1971 the owners agreed to give the most fossil-rich portion of the tract to the Essex County Department of Parks and Recreation. The resulting publicity made the site internationally famous. In 1977 the 17 acres of the present Walter Kidde Dinosaur Park was formally donated to Essex County (Fig. 1) and today the park remains one of the premier sites for Jurassic age fossils in eastern north America. In this paper the 55 acre tract will be called the Riker Hill quarry, and the term Walter Kidde Dinosaur Park will be used for the 17 acre portion of the Riker Hill quarry that is now park.

Although thousands of footprints have been found in Riker Hill quarry, only a tiny fraction have made it into museum collections. Presently, the Walter Kidde Dinosaur Park is administered by the Center for Environmental Studies of the Essex County Department of Parks and Recreation. Several of the tracks found early in the history of the Riker Hill quarry can be seen at the Center (specimen numbers with the prefix ECPC), and permission to collect at the Dinosaur Park should always be sought at the Center for Environmental Studies in advance (Fig. 1). Other repositories of fossils from the dinosaur park, described in this paper, include the American Museum of Natural History (AMNH), and the Yale University Peabody Museum (YPM). Except as noted, the fossils described in this paper were found by Anthony Lessa, Bruce Lordi, and myself, largely between the years 1968 to 1977.

## GEOLOGICAL CONTEXT

Exposed in the Walter Kidde Dinosaur Park are Jurassic age strata of the Triassic-Jurassic Newark rift basin, one of the largest of a vast series of rifts which formed as the supercontinent of Pangea began to break up during the Early Mesozoic (Fig. 2). The sedimentary and volcanic rocks of the exposed eastern North American contingent of these basins are collectively termed the Newark Supergroup (Olsen, 1978; Froelich and Olsen, 1984). The stratigraphy of the Newark Supergroup in the Newark basin is now arguably the best known of any rift of any age thanks to


A
Garden State Parkway
287
80
46
80
46
80
46
95
3
495
280
Walter Kidde Dinosaur Park
Passaic River
Passaic River
Manhattan
95
78
78
Long Island
278
95
Staten Island
Garden State Parkway
5 mi
5 km
B
Walter Kidde Dinosaur Park
Eagle
a
Rock
Ave.
Passaic River
Eisenhower parkway
b
280
280
240
280
320
Riker Hill
440
400
320
360
10
40° 47' 30"
North
200
240
280
320
Northfield Road
Livingston Ave.
280
74° 20' 00"
5000 ft
1500 m
C
Eisenhower Parkway
Morristown and Erie Railroad
Eagle Rock Ave.
Dinosaur Park boundary
Boundary of original Riker Hill quarry tract
300
Township of Roseland
325
275
375
Township of Livingston
400
425
350
325
300
Pleistocene and surfical deposits
Early Jurassic Hook Mt. Basalt
Early Jurassic red Towaco Fm.
Early Jurassic gray Towaco Fm.
Early Jurassic gray Towaco Fm. ("slump beds")
Early Jurassic black Towaco Fm.
500 feet
150 m
Contour interval 25 feet

he collection of over 12 km of core by the Newark Basin Drilling Project and the Army Corps of Engineers (Fig. 3) (for details see Fedosh and Smoot, 1988; Goldberg and others, 1994; Olsen and others , 1995a, 1995b; Olsen and Kent, 1995; Kent and others, 1995, and Goldberg and others, 1994).

For the most part, the Newark basin section can be divided into three main parts: a very thick (>5 km) lower almost entirely Triassic age sedimentary sequence comprised of the Stockton (fluvial), Lockatong (lacustrine), and Passaic (mostly lacustrine) formations; a thinner earliest Jurassic age interbedded lava flow and sedimentary sequence made up of the Orange Mountain Basalt (lava flows), Feltville Formation (mostly lacustrine), Preakness Basalt (mostly lava flows), Towaco Formation (mostly lacustrine), and Hook Mountain Basalt (lava flows); and an upper Jurassic age sedimentary sequence composed of the Boonton Formation (largely lacustrine). Jurassic age strata of the upper Towaco Formation and overlying lower Hook Mountain Basalt are exposed in the Walter Kidde Dinosaur Park (Figs. 3, 4).

The Towaco Formation at the Roseland Quarry consists of relatively fine-grained red, gray, and black units, mostly mudstone and fine sandstone. This facies represents some of the more basinward deposits of the Newark basin Jurassic, although the sequences deposited near the geographic center of the basin have been lost to erosion. The Hook Mountain Basalt as seen in the park is representative of most of its preserved extent.

The entire lacustrine part of the Newark basin section, including the Towaco Formation, consists of a striking pattern of sedimentary cycles caused by the rise and fall of the level of large lakes (Fig. 5) (Olsen, 1986; Olsen and Kent, 1995); they hold the key to the stratigraphic and environmental context of the Dinosaur Park fossils. The sedimentary cycles show up largely as meter-scale alternations of better laminated, often purple, gray, and black mudstones and lighter gray, or more commonly red mudstones and sandstones. These relatively thin alternations are called Van Houten cycles after their discoverer (Van Houten, 1964; Olsen, 1986) and had a period of about 20,000 yr. Variations in Van Houten cycles follow larger cycles called the short modulating cycle (~100,000 yr), the McLaughlin cycle(~400,000 yr), and the long modulating cycle (~2,000,000 yr).(Fig. 5) (Olsen and Kent, 1995). These quasiperiodic cycles were produced by climate changes controlled by celestial mechanics.

The celestial mechanical cycles, and their consequent climate cycles, still operate today. The ~20,000 yr period is the cycle of climatic precession produced by the wobble in the direction of the Earth's axis. This wobble, the result of the gravitational attraction of the sun and moon on the equatorial bulge of the Earth, produces a drift in the season in which we are closest to the sun. The ~100,000 yr, ~400,000 yr, and ~2,000,000 yr cycles are caused by the gravitational interaction of the planets that change the rate of rotation of the figure of the Earth's orbit and the orbit's eccentricity, dramatically altering the magnitude of the effect of the climatic precession cycle. Over the past 600,000 years the ice ages have followed mostly the beat of the ~100,000 year cycle with less important variations following the ~20,000 yr climatic precession cycle and another astronomical cycle of 41,000 yr produced by variations in the angle of the tilt of the Earth's axis (Hays and others, 1976).

During the Triassic and Early Jurassic the Newark basin lay within 3°-10° of the equator (Kent and others, 1995) and the level of the lakes were controlled by the position of the precipitation high along the intertropical convergent zone (Manspeizer, 1982), which in turn was governed by the celestial mechanical cycles (Olsen and Kent, 1995). The 41,000 yr tilt cycle is not important in the Newark lake record because its effects are greatest in higher latitudes. The equatorial biota of the Early Mesozoic followed the cycles of humidity, and the great changes in the distribution of the biota are well seen at the Dinosaur Park.

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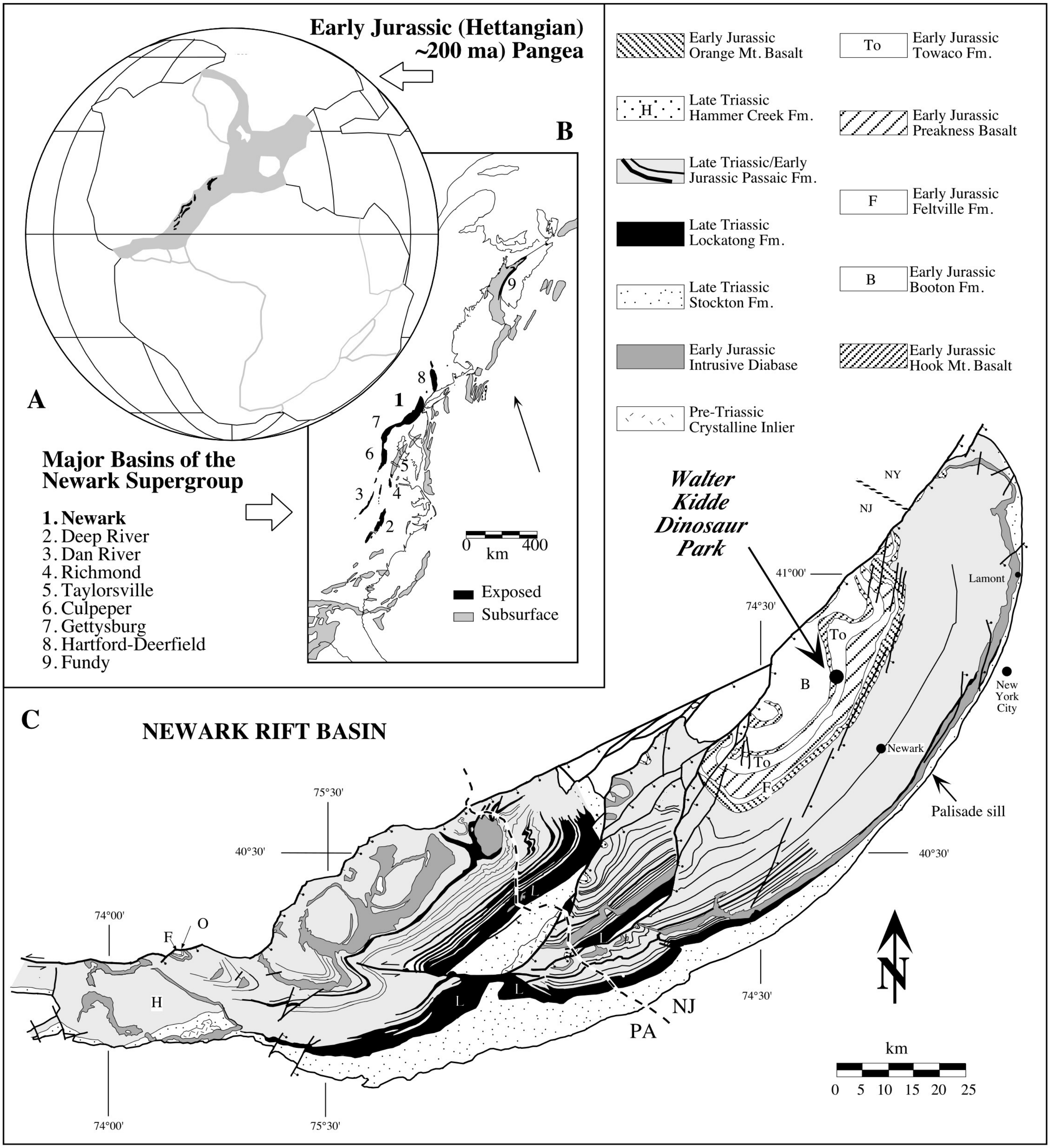
Figure 1. Map of Riker Hill quarry tract and Walter Kidde Dinosaur Park. **A**, Location of park in northwest Essex County, NJ. **B**, Location of Riker Hill quarry on north end of Riker Hill; park can be reached from access road to Arts Center off Beaufort Avenue, which intersects Eisenhower Parkway. Park at the Arts Center and walk to crest of Riker Hill and then down into Walter Kidde Dinosaur Park. The Center for Environmental Studies is at (a) and the Arts Center is at (b). **C**, Geologic map of the Riker Hill quarry and Dinosaur Park. Presently accessible area is within boundary of Walter Kidde Dinosaur park. Adjacent portion of old Riker Hill Quarry is now covered by the Nob Hill residential complex. Topography and cultural boundaries based on map by Bartholomew Associates Inc., ca. 1974.


Early Jurassic (Hettangian)
~200 ma) Pangea
A
B
Major Basins of the
Newark Supergroup
1. Newark
2. Deep River
3. Dan River
4. Richmond
5. Taylorsville
6. Culpeper
7. Gettysburg
8. Hartford-Deerfield
9. Fundy
1
2
3
4
5
6
7
8
9
0
km
400
Exposed
Subsurface
Early Jurassic
Orange Mt. Basalt
H
Late Triassic
Hammer Creek Fm.
Late Triassic/Early
Jurassic Passaic Fm.
Late Triassic
Lockatong Fm.
Late Triassic
Stockton Fm.
Early Jurassic
Intrusive Diabase
Pre-Triassic
Crystalline Inlier
To
Early Jurassic
Towaco Fm.
Early Jurassic
Preakness Basalt
F
Early Jurassic
Feltville Fm.
B
Early Jurassic
Booton Fm.
Early Jurassic
Hook Mt. Basalt
C
NEWARK RIFT BASIN
Walter
Kidde
Dinosaur
Park
NY
NJ
41°00'
74°30'
Lamont
To
B
New
York
City
Newark
To
F
Palisade sill
75°30'
40°30'
40°30'
74°00'
F
O
H
L
L
L
L
NJ
PA
74°30'
N
km
0 5 10 15 20 25
74°00'
75°30'

In more detail, Van Houten cycles consist of three divisions deposited during different phases of the lake rise and fall (Fig. 5), and all of these can be seen at the park. Division 1 was deposited during lake deepening; division 2 was deposited during lake high stand; and division 3 was deposited during lake regression and low stand. In extreme cases, division 2 is a black, organic rich, laminated rock with abundant aquatic fossils, while the surrounding divisions 1 and 3 consist of more massive red and gray beds with reptile footprints, mudcracks, and plant root traces. In less extreme cases, division 2 may consist only of well-bedded red shale with division 1 and 3 composed of massive mudcracked red mudstone.

Through the Triassic age portion of the Newark basin record, Van Houten cycles average close to 4 m thick. In the Jurassic part of the section, however, the cycles are much thicker. As seen in the exposed sections and the ACE cores, the Van Houten cycles in the Towaco Formation average about 25 m thick (30 m at the park). They are somewhat thinner in the underlying Feltville (5-20 m) and over lying Boonton Formation (15 m). The short modulating cycle, the McLaughlin cycle, and the long modulating cycle are corresponding scaled up as well, so much so in fact that a complete long modulating cycle would be a bit thicker than the known Jurassic age sedimentary sequence in the Newark basin.

Prior to the development of the Nob Hill complex on what was the east side of the Riker Hill quarry, the exposed section below the Hook Mountain Basalt consisted of the uppermost red beds of one Van Houten cycle (RVH-1), two complete gray and black shale-bearing Van Houten cycles (RVH-2 and RVH-3), and the lower parts of an entirely red fourth cycle (RVH-4). Together, these cycles constitute most of a short modulating cycle of about 100,000 yr duration. Presently, only the uppermost beds of RVH-3 and RVH-4 are exposed, and thus the exposed sequence represents less than about 40,000 years of Jurassic sedimentation in the drying phase of a 100,000 yr short modulating cycle, which is the drying phase of a 400,000 yr McLaughlin cycle, itself in the wet phase of a 2 my long modulating cycle (Fig. 5). In the following description of the paleontology, all of the fossils will be keyed into the section shown in figure 4 so their positions within the pattern of cyclically shifting climate can be seen.

## PALEONTOLOGY

Varied assemblages of plants and animal remains have been found in the Riker Hill quarry. Most famous are the reptile, notably dinosaur, footprints, but well preserved plants, fish and even insect fossils have been found as well. Below the fossils are described in phylogenetic order, beginning with plants and ending with dinosaurs. This order does not imply a scale of increasing progress, complexity, or degree of evolution and the image invoked should be one of moving along the tips of the branches of a bush, not climbing a tree. I have used the classification of Margulis and Schwartz (1982) for Monera, Protoctista, and plants, Olsen and McCune (1991) for fishes, and Gauthier and others (1988) and Sereno (1991) for the terrestrial vertebrates.

Molecular, body, and trace fossils have been found at the Dinosaur Park. Molecular fossils consists of chemicals from organisms or their chemical breakdown products; hydrocarbons are an excellent example. Body fossils include remain of organisms that preserve part of the form of the organism itself, such as bones, teeth, shells, leaf compressions, silicified wood, and pollen. Trace fossils are products of action of organisms, such as footprints, burrows, root traces, and coprolites. Trace fossils are often called ichnofossils and the formal names given to them are called ichnotaxa. Obviously these are not hard and fast categories; coprolites, for example, can be at once trace fossils of the excrement producer, body fossils in the form of bones

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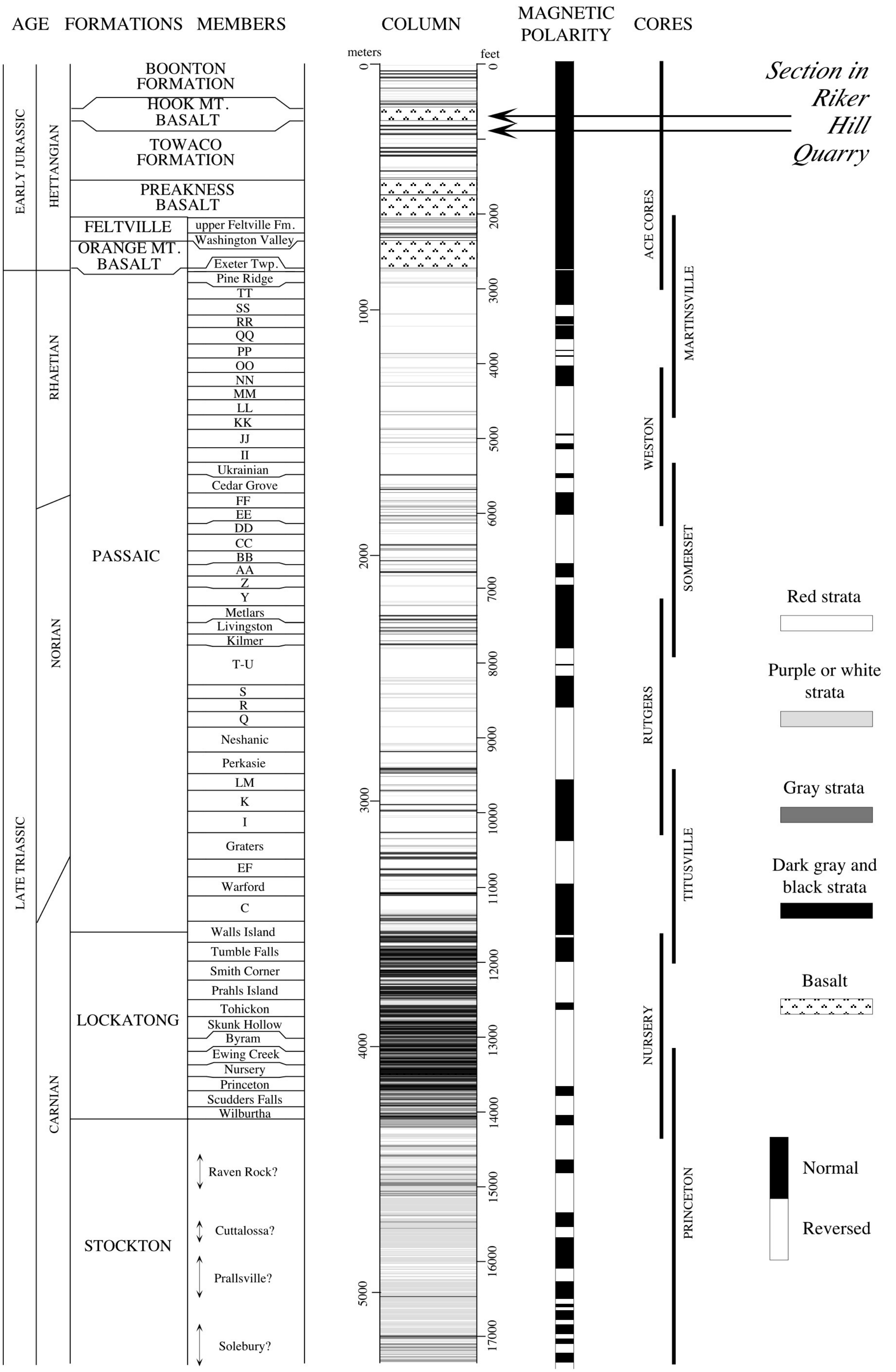
Figure 2. Geological context of the Water Kidde Dinosaur Park. **A**, Configuration of the supercontinent of Pangea in the earliest Jurassic, based on Witte and Kent (1990) and data in Kent and others (1995). Gray area shows region of extensive early Mesozoic rifting, and the black regions are the preserved deposits of the Newark Supergroup. **B**, Distribution of the Newark Supergroup (black); adapted from Olsen and others (1995a). **C**, Geologic map of Newark Basin showing position of the Dinosaur Park; adapted from Olsen and others (1995a).

# NEWARK BASIN SECTION



of prey in the feces, and molecular fossils of the bacteria living in the gut of the predator! At the Dinosaur Park and in the Towaco Formation in general, trace fossils (mostly tracks and burrows) are abundant in the red and gray beds of divisions 1 and 3 of the Van Houten cycles, while most body and molecular fossils are restricted to the gray and black beds of division 2.

Apart from a single tooth fragment and a coprolite, all of the fossils of tetrapods from the Walter Kiddle Dinosaur Park are trace fossils - footprints. Because footprints are the result of an animal interacting with a substrate, the identification and interpretation of footprints is more subtle and difficult than body fossils and requires special discussion. In the case of body fossils, many of the same criteria used to identify a living organism can be applied to a fossil organism as well. This is not the case with footprints, because, the form of footprints is profoundly influenced by behavior of the animal, and the behavior of what the animal walks on, and how the rock breaks as the fossil is collected. In addition, different species of animals often have nearly identical feet, and juveniles often have feet of different proportions than adults. Because of these problems, distinctive kinds of footprints are given their own scientific names, regardless of the animals thought to be responsible. In this way kinds of footprints can be identified and discussed without the added uncertainty of who might have made them. Unfortunately, there is little agreement among specialists in what constitutes distinctive types of footprints that can be given names.

I follow the school established by Peabody (1948) and Baird, (1957) that argues the only criteria useful in identifying and naming footprints are those features that relate directly to the osteology of the trackmaker. This method has the advantage of using similar criteria to those used for body fossils, and hence offers the prospect of using tracks for some of the same types of analyses that body fossils can be used for - biostratigraphy, paleoecology, etc.

In footprints, the osteological characters that can be inferred include the relative lengths, number, and proportions of the digits of the hand (manus) and foot (pes) and the relative position of the articulations between phalanges and the metatarsals and phalanges. In animals that walk upon a foot or a hand, the articulations between the bones are generally underlain by a protective pad (Peabody, 1948; Baird, 1957; Padian and Olsen, 1984). On the other hand, on hand or feet which grasp (such as our hands), the pads are located between the articulations. Thus, in pedal footprints, the location of the articulations between phalanges is roughly in the middle of the pads. In quadrupedal trackways, the same is true for the manus impressions. However, in animals that only put their hands down while resting (e.g. *Anomoepus*,) pads that are adaptations to grasping are likely. These generalizations only apply to medium sized animals, however; very small forms may lack pads altogether, while very large forms may enclose many foot or hand bones in a very large, thick pad.

## Kingdom Monera

The Phylum Monera consists of the prokaryotes, (those organisms lacking a nucleus), and include the heterotrophic, chemosynthetic, and photosynthetic bacteria, which are represented at the park by their molecular remains. At least some of the organic carbon, including the hydrocarbons, in the black shales in cycles RVH-1 and RVH-2 almost certainly has its origin as bacteria, although no remains showing the external form of these organisms have yet been identified.

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Figure 3. Newark basin section showing the stratigraphic position of the Riker Hill quarry section. Newark basin section is based on the results of the Newark Basin Coring Project summarized in Olsen and others (1995a) and Kent and others (1995) and cores collected by the Army Corps of Engineers summarized in Olsen and others (1995b) and Fedosh and Smoot (1988). All of the cores are scaled in thickness to the Rutgers core hole by using the stratigraphic overlap zone between cores.

## **Kingdom Protoctista**

### PHYLUM CHLOROPHYTA (green algae)

Pratt and others (1988) described the occurrence of β-carotane in cycles RVH-2 and RVH-3 (units 28 and 23c). β-carotane is the degradation product of pigments of a variety of single celled algae. In the fossil cases that have been examined in detail the most prevalent group are the micro green algae (Collister and others, 1992), which are also probably the major source of the oil seen in the Towaco Formation as well (Hartgers and others, 1994) (Fig. 6). Both the β-carotane and the oil represent molecular fossils of that group of algae at the Riker Hill quarry. The preservation of β-carotene also indicates how little the sedimentary rocks of the Towaco formation have been thermally altered, in marked contrast to older parts of the Newark basin sedimentary record (Walters and Kotra, 1990).

## **Kingdom Plantae** (multicellular green plants)

### PHYLUM SPHENOPHYTA (horse tail rushes and quillworts)

*Equisetites* sp.

The fossil horsetail rush *Equisetites* is one of the more common recognizable plant fossil found at the park. It is easily identified by its segmented and ridged stems. Unfortunately, no Riker Hill quarry examples have made their way into permanent collections or have been photographed.

### PHYLUM PTERIDOPHYTA (ferns)

Organ taxa *Cladophlebis* sp., *Clathropteris sp.*, *Dictyophyllites* sp.,
*Converrucosisporites cameronii*

Leaf and pinule fragments of the fern *Cladophlebis* sp., and the dipteraceous fern *Clathropteris* have been found in the gray mudstones at the park. Fragments of *Cladophlebis* and similar ferns are recognized by their delicate branching of leaf veins and pinnules (leaflet stems) even when no leaf tissue is preserved. *Clathropteris*, on the other hand, has thick leaves with veins organized into rectangles producing a quilted look. Leaf fragments are usually rectangular, with ribs following the venation. The spore taxa *Dictyophyllites* sp. and *Converrucosisporites cameronii* have been identified by Cornet (pers. comm., 1974) from unit 9-10. Cornet (1977) has identified *Clathropteris* as the producer of *Converrucosisporites cameronii* .

### PHYLUM CONIFEROPHYTA (conifers)

Cheirolepidaceae

Organ taxa *Pagiophyllum* spp., *Brachyphyllum* spp. (in part),
*Corollina meyeriana*

By far the most abundant recognizable plant remains at the Riker Hill quarry are those of the extinct cheirolepidaceous conifers (Fig. 6). These were the dominant land plants in the tropical regions from around the Triassic-Jurassic boundary to the beginning of the Late Cretaceous, a span of over 140 my. Cheirolepidaceous conifers tended to have short fleshy leaves with a thick cuticle. These leave are commonly found on isolated shoots, suggesting the plant may have been in some cases deciduous. Short leafed forms are called *Brachyphyllum* and long leafed forms *Pagiophyllum* . In the Towaco forms the female cones were relatively small (4-10 cm) and the male (pollen) cones were about 1 cm (Fig. 6). The pollen of these conifers (*Corollina*) consists of globes with a thickened rim with grains often grouped into tetrads (Fig. 6). The wood lacks vessels and distinctive characteristics and the habit of the plants may have ranged from shrubs to very large trees.

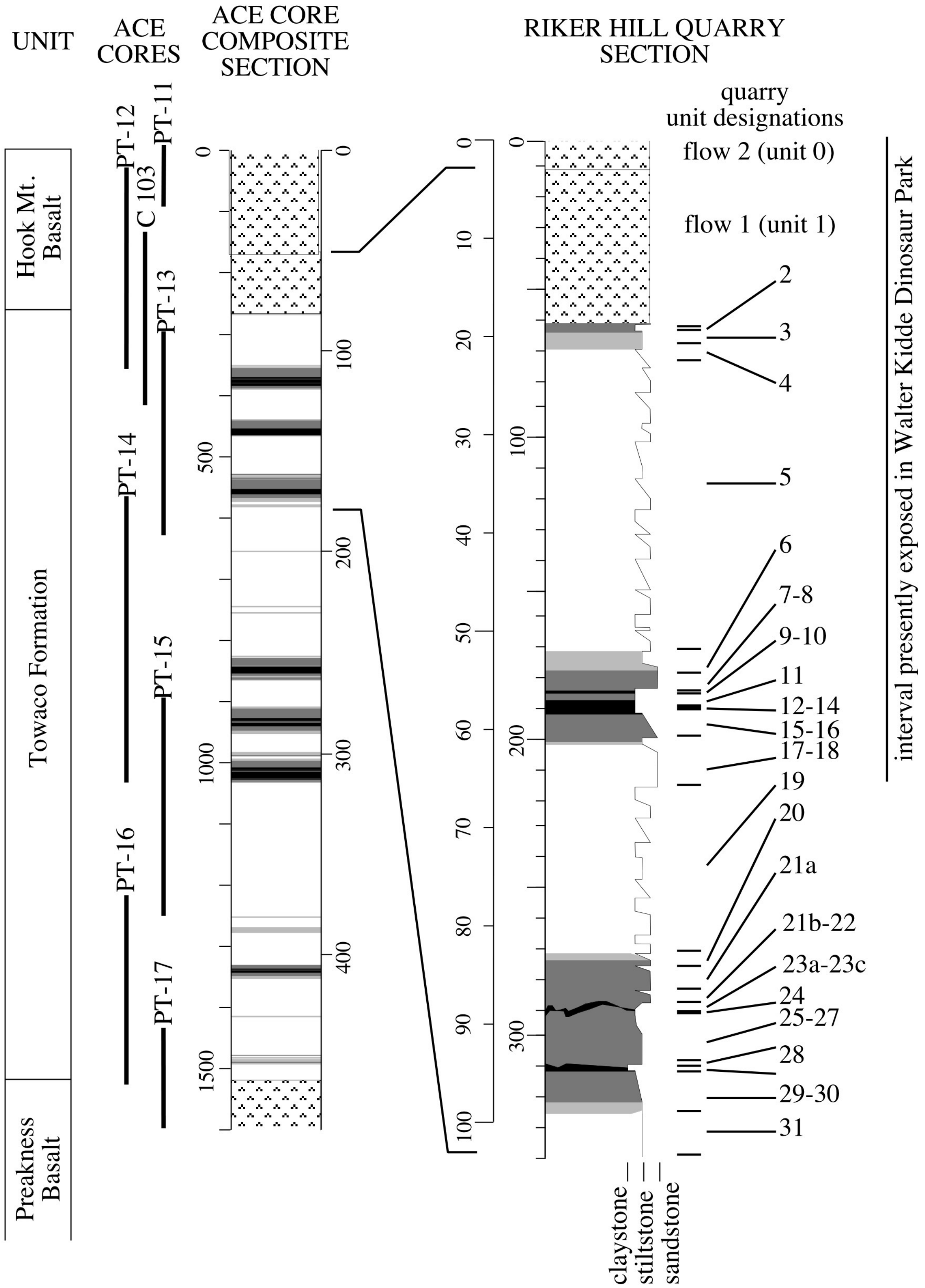
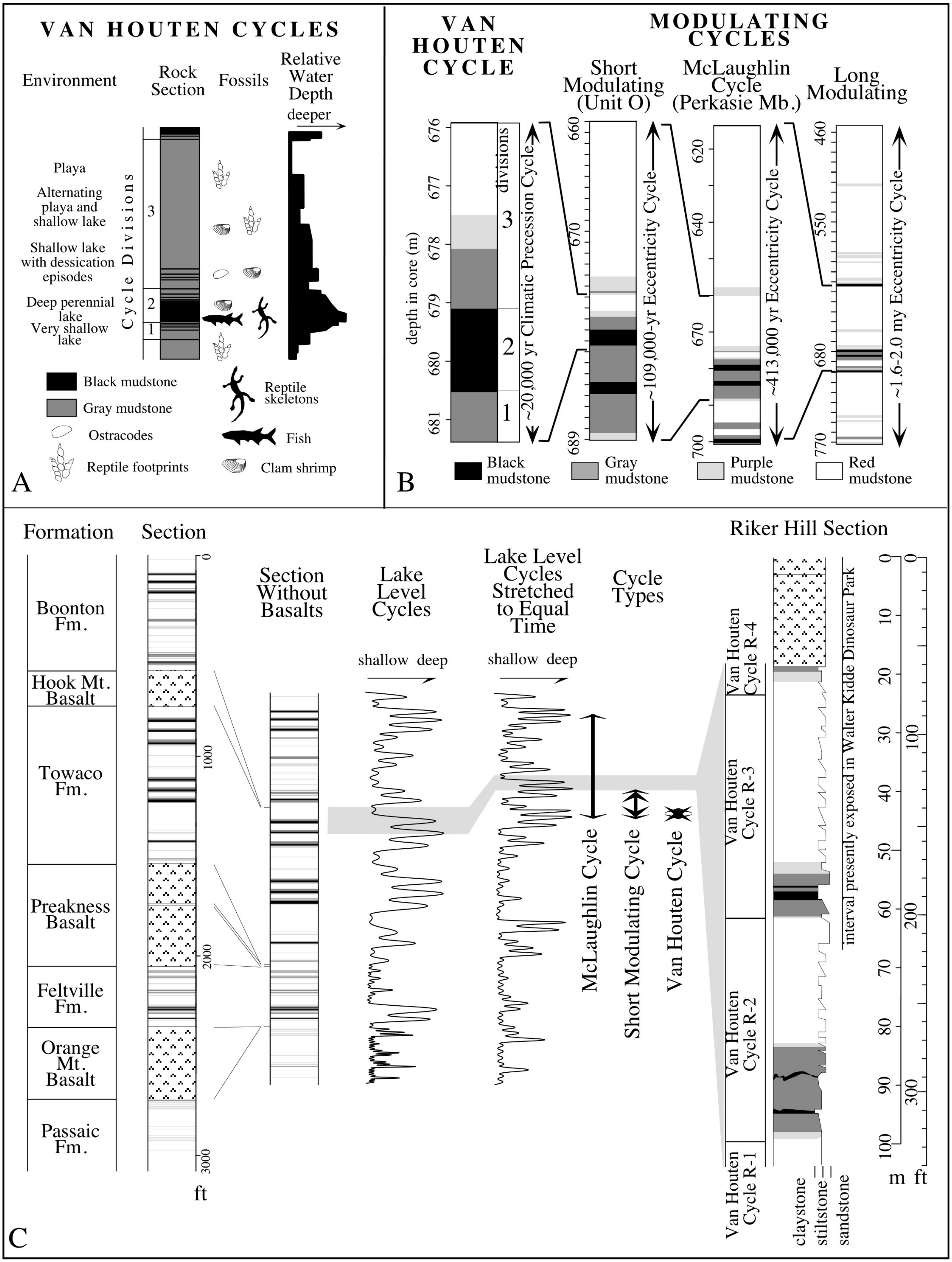


Figure 4. Section in old Riker Hill quarry compared to reference section of the Towaco Formation from the Army Corps of Engineers cores; from Olsen and others (1995b). Unit designations are referred to in text. Key to lithologies as in figure 3. Original quarry section described in Olsen (1975).


VAN HOUTEN CYCLES
Environment
Rock Section
Fossils
Relative Water Depth
deeper
Playa
Alternating playa and shallow lake
Shallow lake with dessication episodes
Deep perennial lake
Very shallow lake
Cycle Divisions
3
2
1
Black mudstone
Gray mudstone
Ostracodes
Reptile footprints
Reptile skeletons
Fish
Clam shrimp
A
VAN HOUTEN CYCLE
MODULATING CYCLES
Short Modulating (Unit O)
McLaughlin Cycle (Perkasie Mb.)
Long Modulating
depth in core (m)
676
677
678
679
680
681
divisions
~20,000 yr Climatic Precession Cycle
660
670
689
~109,000-yr Eccentricity Cycle
620
640
670
700
~413,000 yr Eccentricity Cycle
460
550
680
770
~1.6-2.0 my Eccentricity Cycle
Black mudstone
Gray mudstone
Purple mudstone
Red mudstone
B
Formation
Section
Boonton Fm.
Hook Mt. Basalt
Towaco Fm.
Preakness Basalt
Feltville Fm.
Orange Mt. Basalt
Passaic Fm.
0
1000
2000
3000
ft
Section Without Basalts
Lake Level Cycles
Lake Level Cycles Stretched to Equal Time
shallow deep
shallow deep
Cycle Types
McLaughlin Cycle
Short Modulating Cycle
Van Houten Cycle
Riker Hill Section
Van Houten Cycle R-4
Van Houten Cycle R-3
Van Houten Cycle R-2
Van Houten Cycle R-1
interval presently exposed in Walter Kidde Dinosaur Park
claystone
siltstone
sandstone
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
m ft
C

As is common in paleobotany, different names for these plant organs of the cheirolepidaceous conifers are used because they are not often found together and indistinguishable organs forms may be found in a wide variety of plant species. For example, the leaf genus *Brachyphyllum*, not only includes conifers belonging to the Cheirolepidaceae, but also includes some foliage that might belong to Auricaurian conifers (as below). Likewise there are many more foliage types of cheirolepidaceous conifers than there are cheirolepidaceous pollen types. The only way to tease out the taxonomic significance of all the morphological variation is to find different organs attached to one another. This has been done by Cornet (1977) who has found many associated organ taxa and so we are fairly certain of the affinities of the forms listed here.

Remains of cheirolepidaceous conifers are the most common plant fossils in all facies at Riker Hill. Compressed wood (Fig 6G). and fossil charcoal almost certainly belonging to these plants are found in all of the gray and blacks beds at the park, and large roots are present the gray siltstones and sandstones of unit 16 of division 1 of cycle RVH-3. Leaf and shoot compressions and cone fragments are similarly present in all the gray beds, and well preserved material occurs in units 9 and 10 of division 2 of cycle RVH-3 (Fig. 6), which is still exposed.

Impressions of leafy shoots, and clay casts of roots and stems are common in the red units, sometimes on the same surfaces bearing footprints (Fig. 6). *Imponoglyphus torquendus* was originally described from Late Triassic age strata of the former Soviet Union and an example of this form species has been described from the Dinosaur Park by Metz (1984). This form species consists of impressions similar to truncated cones fitted into one another. *Imponoglyphus torquendus* is a almost certainly an impression of a conifer shoot similar to that in figure 6.

From the extreme dominance of the remains of cheirolepidaceous conifers in all facies at the park it is clear that the woodlands and scrub lands of the Early Jurassic during deposition of the Towaco Formation were strongly dominated in biomass by the cheirolepidaceous conifers. However, it is not yet possible to tell how many biological species of cheirolepidaceous conifers are represented, and the species diversity could be quite low.

### Araucariacae (monkey puzzle tree and relatives)

### Organ taxa *Brachyphyllum* spp. (in part), *Araucariacites australis* (pollen)

No definitive foliage or cone material referable to araucarian conifers have been identified at the Riker Hill quarry, however , they are almost certainly present as araucarian pollen is preserved at the site. Generally, the leaves of araucarian conifers are thicker and have a different arrangement than those of the Cheirolepidaceae (Fig. 6). Although the leafy shoots of the two plant groups may be hard to distinguish, the putative pollen of the araucarians at Riker Hill (*Araucariacites australis*) is completely different than that of cheirolepidaceous conifers, being of bisaccate form, more similar to that of pine (Fig. 6). The name *Araucariacites australis* highlights its similarity to araucarian pollen, however, the lack of a demonstrated association of the pollen with appropriate cones and foliage makes this assignment only a plausibility. Although araucarian conifers were a relatively minor part of the Early Mesozoic during Towaco Formation time (based on the pollen) they do survive today in the southern hemisphere, with the popular house plant, the monkey puzzle tree being a common example.

Figure 5. Cyclostratigraphy of the Riker Hill quarry and Water Kidde Dinosaur Park. **A**, Basic Van Houten cycle cause by the ~20,000 year cycle of climatic precession. This cycle is from the Lockatong Formation of Byram, NJ; adapted from Olsen and Kent (1995). **B**, Modulating cycles of the Newark basin. This example is from the middle Passaic Formation (Rutgers core) from Olsen and Kent (1995). **C**, Cartoon of the cyclostratigraphy of the Newark basin Jurassic section. Lithologic section based on the Army Corps of Engineers cores. Note the general similarity of pattern to (B) above.

## PHYLUM CYCADOPHYTA (cycads and cycad-like seed plants)
### Organ genera *Otozamites* sp., *Cycadopites* sp.

The Cycadophyta are a group of plants including the extinct Bennettitales and the superficially similar extant cycads. Rare elongate triangle-shaped leaves attributable to the Cycadophyte foliage genus *Otozamites* have been found in the Dinosaur Park in unit 10 of cycle RVH-3. These leaves resemble those of some living some cycads, such as the common house plant *Zamia*. The pollen genus *Cycadopites* may have been produced by Bennettitales such as *Otozamites* (Fig. 6). These plants seem to have been low shrubs, perhaps as common as ferns during deposition of the Towaco Formation.

## **Kingdom Animalia** *incertae sedis* (uncertain classification)
### Ichnotaxa *Cochlichnus anguineus, Helminthopsis* sp., *Planolites montanus, Planolites beverleyensis Trepyichnus bifircus, Biformites* sp., *Fustiglyphus roselandensis, Scoyenia gracilis*

A rich invertebrate trace fossil assemblage has been recovered over the years from the Riker Hill quarry, mostly from strata exposed in the Dinosaur Park. As described by Metz (1992) *Cochlichnus anguineus* consists of smooth, narrow (1.5-2 mm), sinusoidal, unlined, and unbranching horizontal burrows possibly made by nematodes or perhaps fly larvae. *Helminthopsis* sp. described by Metz (1991), is a smooth, straight to gently winding burrow of constant width that does not show sediment layer crossings. It may possibly have been produced by a worm-like form. Metz (1992) has described two species of *Planolites*, a form genus is comprised of small, horizontal or inclined filled burrows lacking exterior ornament or interior structure. *Planolites montanus* is a very small form (1-1.5 mm) having occasionally branching burrows, often curving, filled with material coarser than the matrix, and with crossovers and interpenetrations (Metz, 1991),. *Planolites beverleyensis* is a larger (5-6 mm) burrow that is similar in form and filling of *P. montanus*, but shows discontinuous rings were the burrow tapers (Metz, 1991). A perhaps similar form is shown in figure 7. In this case a burrow is present which shows distinct annuli which apparently was broken up at one end releasing pellets which were scattered by a weak current. In general, however, *Planolites* is a catch-all form with little character that could have been made by variety of worms or even arthropods. *Trepyichnus bifircus* , as described by Metz (1991), consists of a "... straight to curved trace (1 mm in diameter), with short extensions (1 mm - 2 mm) possessing slightly thickened terminations projecting from junctures between longer segments, creating a zig-zag pattern". The originator of this kind of trace is unknown. *Biformites* sp. and *Fustiglyphus roselandensis* are possibly related forms described by Boyer (1979) from the Riker Hill quarry. *Fustiglyphus* consists of two kinds

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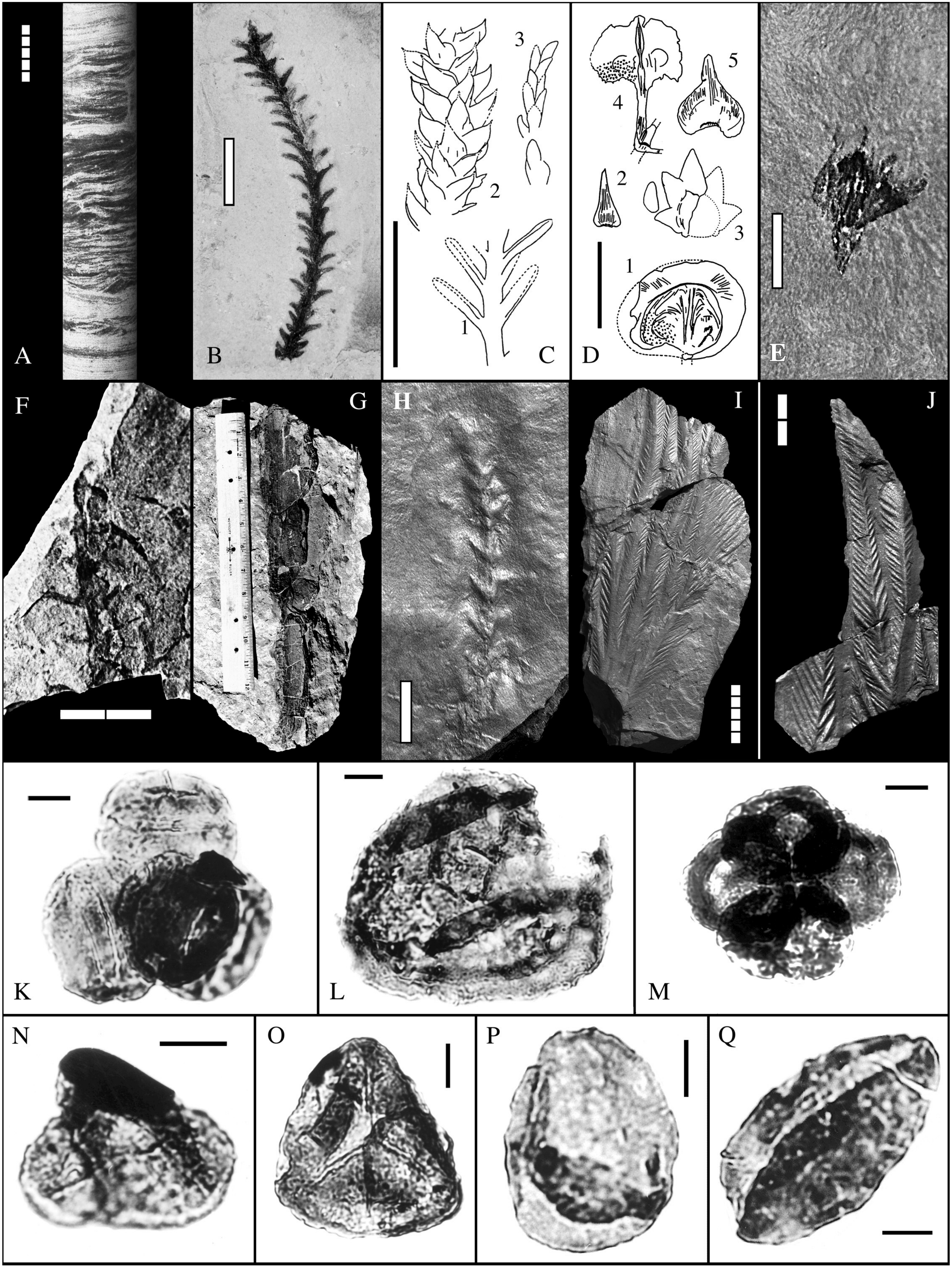
Figure 6. Molecular and plant body (organ) fossils from the Riker Hill Quarry. **A**, Portion of Army Corps of Engineers core of the upper Towaco Formation showing oil staining in a pale gray fine rippled sandstone (molecular fossil) (scale, 5 cm). **B**. *Pagiophyllum* sp.- example of compression from Portland Formation; similar examples of conifer shoots have been found at the Dinosaur Park, but none have been photographed or archived in museum collections (scale, 1 cm). **C**, Conifer shoots from the Towaco Formation (adapted from Olsen and others (1989) (scale, 1 cm): 1, *Pagiophyllum* sp. 7a, from the Dinosaur Park (unit 10); 2, *Pagiophyllum* sp. 8p from the middle Towaco Formation of Pompton, NJ; 3, *Pagiophyllum* sp. 5p, equivalent unit to gray part of cycle RVH-3, from Toms Point, Lincoln Park, NJ. **D**, Conifer Cone parts (adapted from Cornet, 1977) (scale, 1 cm): 1, cone scale seed complex from gray part of cycle equivalent to RVH- 3 in Hartford basin, Rt. 9/91 road cut, Cromwell, CT; 2, Cone scale bract, unit 10, Dinosaur Park; 3, partly reconstructed cone scale bearing ovule, unit 10, Dinosaur Park; 4, cone scale bract and seed(?), unit 10, Dinosaur Park; 5, cone bract, unit ?10, Dinosaur Park (scale, 1 cm). **E**, partial cone scale bract complex, unit 10 (scale, 2 m), Riker Hill quarry; **F**, fragmentary cone axis, unit 10, Dinosaur Park ( scale, 2 cm).. **G**, small compressed log, gray part of cycle RVH-2, Riker Hill Quarry (ruler is 1 ft). **H**, impression of *Brachyphyllum* shoot, upper unit 5, Dinosaur Park (scale, 1 cm). **I**, large set of rill marks (not a fossil) (scale, 5 cm); **J**, small piece of rill marks showing fine detail (scale, 2 cm). **K-Q**, pollen and spores from unit 9-10, courtesy of Bruce Cornet (pers. com., 1994), (scale, 10 microns) Dinosaur Park: **K**, cheirolepidaceous conifer pollen, *Corollina meyeriana*, tetrad; **L**, possible araucarian pollen, *Araucariacites australis;* **M**, cheirolepidaceous conifer pollen, *Corollina meyeriana*, tetrad, **N**, spore of fern *Clathropteris*, *Converrucosisporites cameronii*; **O** and **P**, fern spore, *Dictyophyllidites* sp.; **Q**, cycadophyte pollen, *Cycadopites* sp.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of linked trails: a thin (0.4-0.6 mm) part 4-7 mm long with distinct annulations and a thicker (2-2.5 mm) part 2 to 3 mm long with faint annulations. There is a faint grove running down the middle of the trace. *Biformites* is a tapering trace with annulations and a faint longitudinal groove. According to Boyer (1979) the Roseland *Fustiglyphus* is a succession of repeated *Biformites* -like traces, probably produced by a small arthropod seeking refuge in a deteriorating environment.

Metz (1992) has described *Scoyenia gracilis* from the Dinosaur Park, where it is not common. *Scoyenia* is a lined burrow with a menisicate filling and distinct rice-grain-like prod marks on the outside surface. This form genus is the most common trace fossil in deposits of Triassic age in the Newark basin (and Newark Supergroup). It is markedly more rare in Newark Jurassic strata, especially in the Towaco Formation. There is little consensus on the makers of *Scoyenia* with opinions ranging from polychaete worms (D'Alessandro, and others, 1987), to insects (Frey and others, 1984), and crayfish (Olsen, 1988). This burrow form is very badly in need of detailed study.

## PHYLUM ARTHROPODA
### Class Insecta (insects)
### Order Coleoptera (beetles)
### Archostemata (stem beetles)
### Family Cupedidae (reticulated beetles)
### *Liassocupes* sp.

Body fossils of insects are represented by a single beetle elytron (wing cover) from unit 10. The rows of punctures between narrow ridges and the general shape of the elytron distinguishes the beetle family Cupedidae, hence the common name "reticulated" beetles. The elytron from the Dinosaur Park most closely resembles the Early Jurassic genus *Liassocupes* (Fig. 7C) (Whalley, 1985). The cupedids are often regarded as the most primitive of beetle families. The family is still extant with both larvae and adults feeding on rotting wood. *Cupes concolor* is the most common living member of the family in the United States and is very similar to the Dinosaur Park fossil.

This isolated elytron from the park is illustrative of how incomplete our sampling of Early Jurassic life is. Then as now, beetles were probably the most diverse insect group and insects the most diverse animal group. The lack of insect fossils is probably due to both a real bias against fossilization and a collection bias. Recent years has seen a strong increase in the number of fossil insect body fossil occurrences within the Newark Supergroup (Olsen, 1988; McDonald and Huber, 1995) and there is no reason not to expect more finds at the Dinosaur Park (especially with intense collecting of unit 10).

### Order ?Coleptera (beetles)
### Ichnogenus *Acanthichnus* sp.

Several trackways attributable to Hitchcock's ichnogenus *Acanthichnus* have been found at the Dinosaur Park (Fig. 7). This ichnogenus is distinguished by two rows of thin impressions. These kinds of tracks could be made by any of a number of kinds of walking insects. The well

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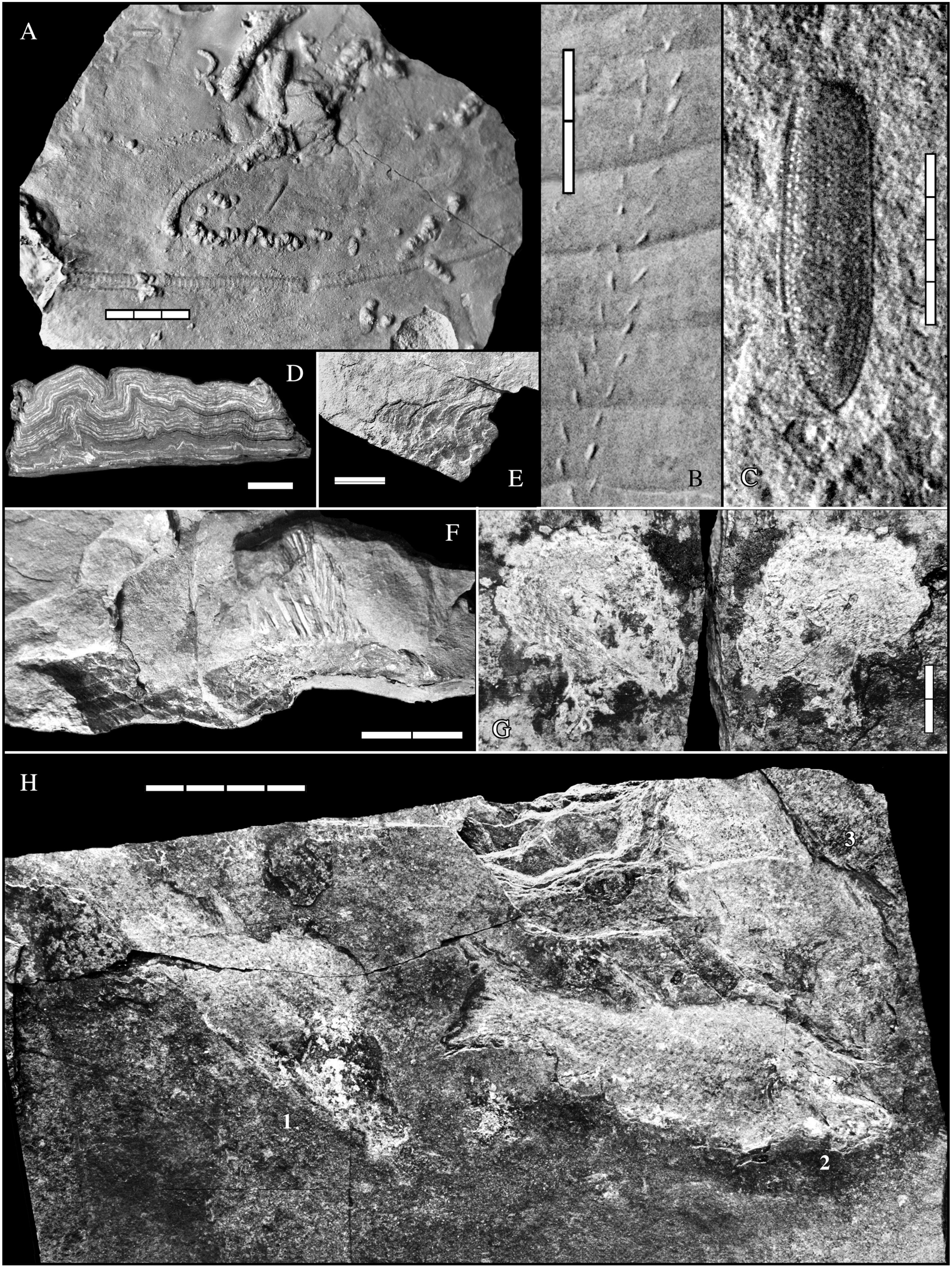
Figure 7. Invertebrates and fish from the Riker Hill Quarry. **A**, unusual, unidentified burrow (scale, 3 cm) from unit 5, Dinosaur Park; **B**, insect walking trace, *Acanthichnus* sp., from low in unit 5, Dinosaur Park; **C**, beetle elytron (wing cover), *Liassocupes* sp., unit 10, Dinosaur Park (specimen in YPM collection) (scale, 4 mm); **D**, Folded microlaminated D, folded microlaminated β-carotane-bearing black shale of unit 13 (scale, 1 cm); **E**, fragment of back of fish with dorsal ridge scales of *Semionotus tenuiceps* group semionotid (scale, 1 cm); **F**, Three dimensional example of indeterminate *Semionotus* sp., from unit 23b, Riker Hill quarry (scale, 2 cm). **G**, Curled up part and counterpart of Semionotus sp. from unit 23c (YPM 6472). **H**, three *Semionotus* from unit 23b, Riker Hill quarry; one on left (1) is of the *Semionotus tenuiceps* group, while the other two (2&3) are indeterminate.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defined trackways in figure 7B come from lower unit 5 which has very small oscillatory ripples characteristic of very shallow water.

PHYLUM CHORDATA (notochord-bearing animals)
Class Osteichthyes (bony fishes)
Subclass Actinopterygii (ray finned fishes)
Order Holosteii (holostean fishes)
Family Semionotidae
*Semionotus* spp.

The only fish genus found thus far at the park is the holostean *Semionotus* , the most abundant fish throughout the Newark Supergroup Jurassic. *Semionotus* has been found in four units in the Riker Hill quarry section (Fig. 4). Cycle 3 has produced articulated fish in the upper microlaminated zone (unit 23c) and the overlying platy fine sandstone (unit 23b) of division 2. Fish fragments have been found in Cycle 2 in the gray claystone that produced the beetle elytron (unit 10) in division 2 and in a coprolite in the lower part of division 3 (lower unit 5).

*Semionotus* is a member of the family Semionotidae, which appears to be closely allied to the living gar family (Lepisosteidae) (Figs. 7, 8). Both groups have inherited from their ancestors the primitive condition of hard bony, rectangular ganoid scales and a hemiheterocercal caudal fin with a small upward pointing fleshy lobe. Both groups are distinguished by having a very similar row of bony plates in front of the eye, shielding the snout. Unlike gars, however, semionotids lack a very long, alligator-like snout. *Semionotus*, itself, is distinguished by having a modified row of spine-bearing scales between the head and dorsal fin. These so called dorsal ridge scales vary greatly between different species of Semionotus, and, along with body shape, help in recognizing different species (Olsen and others, 1982; McCune, 1987a, 1987b).

So far, the Towaco Formation as a whole has produced only *Semionotus*. It is very unusual for lakes, especially large ones, to have only one genus, and other genera are probably present but in low abundance. Studies of thousands of well-preserved *Semionotus* from the Towaco Formation of Pompton, NJ by McCune (1987a, 1987b) shows that although the genus-level diversity is very low, the species level diversity may be very high. McCune has identified over 30 species of *Semionotus* in a laminated division 2 of a single Van Houten cycle. This kind of high species diversity in one genus in a geographically circumscribed area is termed a species flock. Closely analogous species flocks of cichlid fishes occur today in the great lakes of Africa, and species flocks of the fruit fly *Drosophila* occur in Hawaii. In these modern cases, the high species diversity correlates with local deficits in the generic diversity due to geographic isolation.

At the Riker Hill quarry, at least three species of *Semionotus* appear present, although the preservation is too incomplete for certain identification. These are *Semionotus tenuiceps,* a small thin bodied, small dorsal ridge scaled form, and a large form. *Semionotus tenuiceps* has a distinct hump in back of the head and expanded shield-like dorsal ridge scales. The two other forms are much too poorly preserved to be assigned to known species.

Preservation of the *Semionotus* at the park is variable. Fish from unit 23c in division 2 of cycle RVH-2 are preserved as flat films. No bone appears to be preserved, although an organic matrix outlines the gut and eye regions. The mineral matter of bone is a form a calcium phosphate (hydroxylapatite). Generally, in the process of fossilization the cellular spaces within

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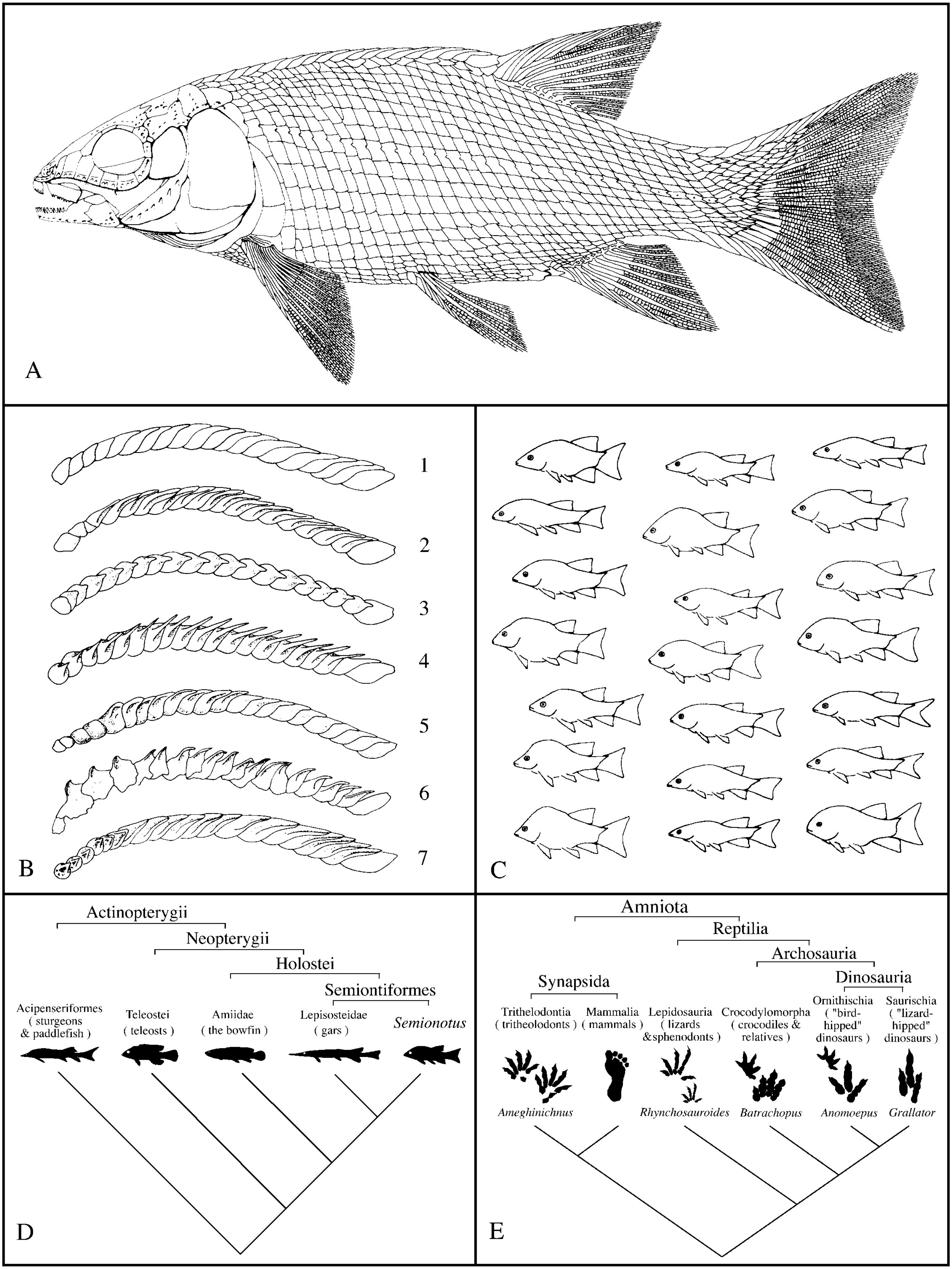
Figure 8. *Semionotus*, fish relationships and tetrapod relationships for the Riker Hill quarry. **A**, Reconstruction of member of the *Semionotus elegans* group of *Semionotus* from the Boonton Formation of Boonton, NJ (from Olsen and McCune, 1991), the form of which is representative of Riker Hill quarry specimens in general. **B**, Different kinds of dorsal ridge scale types that distinguish *Semionotus* species groups in Towaco Formation (modified from McCune and others (1984) - examples are: 1, "simple scale group"; 2, "modified simple scale group"; 3, "small scale group"; 4, *Semionotus micropterus* group; 5, "globular scale" group; 6, *Semionotus tenuiceps* group; 7, *Semionotus elagans* group. Only the *Semionotus tenuiceps* group is positively identified at Riker Hill. **C**, Body forms of *Semionotus* from the Towaco Formation (Cycle "P4") of Pompton, NJ (adapted from McCune and others, 1984). These forms differ from each other in scale counts, fin ray counts, tooth shape, dorsal ridge scale type, as well as body shape. **D**, Relationships of *Semionotus* within the Actinopterygii (ray finned fishes) (from relationships in Olsen and McCune, 1991). **E**, Relationships of groups represented by footprints at Riker Hill within the Tetrapoda.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Actinopterygii
Neopterygii
Holostei
Semiontiformes
Acipenseriformes ( sturgeons & paddlefish )
Teleostei ( teleosts )
Amiidae ( the bowfin )
Lepisosteidae ( gars )
*Semionotus*
E
Amniota
Reptilia
Archosauria
Dinosauria
Synapsida
Trithelodontia ( tritheolodonts )
Mammalia ( mammals )
Lepidosauria ( lizards &sphenodonts )
Crocodylomorpha ( crocodiles & relatives )
Ornithischia ( "bird-hipped" dinosaurs )
Saurischia ( "lizard-hipped" dinosaurs )
*Ameghinichnus*
*Rhynchosauroides*
*Batrachopus*
*Anomoepus*
*Grallator*

the bone become filled with minerals brought in through ground water (often calcite) and the original mineral matter of the bone becomes somewhat altered to carbonate fluorapatite (i.e. francolite) (Shemesh, 1990). In anoxic environments degradation products of the organic matrix of the bone also remain, coloring the bone black. In the case of the *Semionotus* in unit 23c, the phosphate mineral matter of the bone has been dissolved away, leaving the residuum of the organic matrix of the bone and organic matter in the gut as an outline. This dephosphatization has been observed elsewhere in the Newark Supergroup and is generally more prevalent in the portions of lacustrine strata farther from the basin edge. A completely different style of preservation is represented by the fish from unit 23b, in which siltstone and fine sandstone have preserved the fish as a natural mold in high relief (Fig. 7). In this case the bone tissue has been dissolved through recent, near-surface weathering.

Bone is preserved (along with the decay products of the organic matrix) in the *Semionotus* fragments from unit 10 in division 2 of cycle RVH-3. Bone is also preserved in the fish fragments in a coprolite from lower unit 5 in the lower part of division 3 of cycle RVH-3, however, the organic matrix is not preserved in the red mudstones, and hence the bone is white. The coprolite itself may well be the excrement of a small theropod dinosaur.

### Tetrapoda (four footed vertebrates)
### Amniota (tetrapods with an amniotic egg)
### Synapsida (amniotes with only a lower temporal opening)
### Therapsida (synapsids with reduced phalangeal formula)
### Mammaliformes *incertae sedis*
### Ichnogenus *Ameghinichnus*
### *Ameghinichnus* n. sp.

The ichnogenus *Ameghinichnus* was established by Casamiquela in 1961 on the basis of small five toed quadrupedal tracks from the Late Jurassic Maltilde Formation of northern Santa Cruz in Argentina, which he named *Ameghinichnus patagonicus* (Casamiquela, 1964). This genus is characterized by a pentadactyl manus and pes of equal size with nearly symmetrically disposed digits of subequal length (Fig. 9). Although the type species is preserved in medium-grained sandstone and the phalangeal pads are not clearly visible, the shapes of the digits are consistent with a phalangeal formula of 2, 3, 3, 3, 3 in both the manus and the pes (Fig. 9). This phalangeal formula is seen only in the advanced therapsid synapsids, the group of amniotes that includes mammals, and Casamiquela assigned *Ameghinichnus* to the latter group. The trackways

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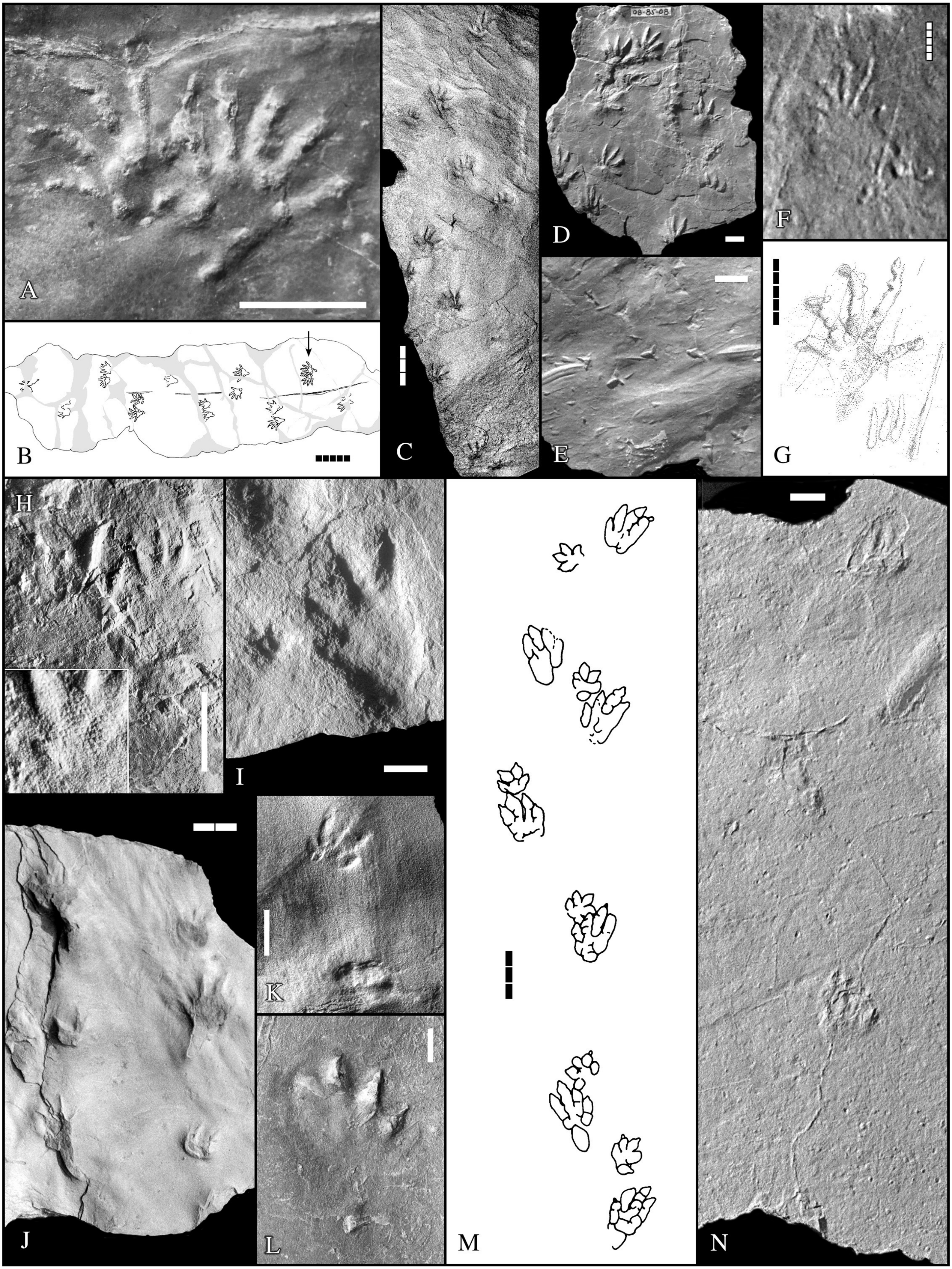
Figure 9. Quadrupedal tracks from the Riker Hill quarry. **A**, Right manus-pes set of *Ameghinichnus* n. sp. from upper unit 5, Dinosaur Park (AMNH 29298, collected by Larry Felder, 1978). Manus is on left and pes is on right. **B**, Drawing of trackway of *Ameghinichnus* n. sp. Arrow shows manus pes set in A (above). **C**, Underprint trackway of *Ameghinichnus* from upper unit 5, Dinosaur Park (Charles Rizzo collector, Charles Rizzo collection) (scale, 3 cm). **D**, Natural cast of deep underprints of at least one trackway of *Ameghinichnus* from upper unit 5, Dinosaur Park (Charles Rizzo collector, Charles Rizzo collection). **E**, Natural casts of molds of dissolved halite crystals, unit 11, Dinosaur Park (Robert Salkin collector, Robert Salkin collection). **F**, Right manus-pes set of *Rhynchosauroides* n. sp., from uppermost Towaco Formation, Lincoln Park, NJ (John Colegrande collector, PU 18563) (scale, 5 mm). Manus is very faint, below and to right of hand-like pes. **G**, Drawing of same specimen as F (above) (scale, 5 mm). **H**, Natural cast of right manus-pes set. with at least one other additional superimposed pedes, of *Batrachopus* sp., unit 5, Dinosaur Park (Charles Rizzo collector, Charles Rizzo collection) (scale, 1 cm). Inset shows detail of scale impression on manus. **I**, Underprint of manus-pes set of *Batrachopus* sp., unit 5, Dinosaur Park (Charles Rizzo collector, Charles Rizzo collection) (scale 1 cm). Manus impression is incomplete. **J,** Very deep underprint of ?*Batrachopus* sp. from rubble, Riker Hill quarry (specimen lost). Note deep impression of heel area. **K**, Manus and partial pes impression of *Batrachopus* sp. from unit 5, Dinosaur Park (Charles Rizzo collector, Charles Rizzo collection) (scale 1 cm). **L**, *Batrachopus dispar* pes from the Vreeland Quarry, stratigraphic equivalent to unit 5 at Riker Hill (Rutgers New Brunswick Museum main display slab) (scale 1 cm). **M**, Type specimen of *Batrachopus dispar* probably from the East Berlin Formation of Mount Tom, Massachusetts (AC 26/5 and 26/6) (scale, 3 cm) (from Olsen and Padian, 1986). Note impressions of heel. **N**, Trackway of *Batrachopus* from same slab as figure 12K, Riker Hill quarry, collector and disposition unknown (scale 1 cm).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of *Ameghinichnus patagonicus* show that, in addition to normal quadrupedal progression, it frequently galloped and hopped.

In 1978 Mr. Larry Felder found a superb trackway of *Ameghinichnus* in the upper beds of unit 5 of the Dinosaur Park. Subsequently, several additional specimens have been collected. The Dinosaur Park form shows the phalangeal pads more clearly than in the type species, the therapsid phalangeal formula of 2, 3, 3, 3, 3 is definitely present (Fig. 9). The new form differs from *A. patagonicus* in having a more elongate calcanar heel on the lateral side of the pes and in having a slightly more asymmetrical manus (Fig. 9). Since the discovery by Mr. Felder, several more specimens of *Ameghinichnus* have been recovered from closely adjacent beds, although all of these are underprints (Fig. 9). The form appears to be fairly common in the interval in these beds. A complete treatment of this new species will be given elsewhere,

Although the inferred structure of the manus and pes are consistent with mammals in both the type and new species, this arrangement appears phylogenetically well below the base of the Mammalia. In fact, such tracks could have been made by any of a variety of advanced therapsids, including the tritylodonts, which were contemporaneous with both track forms, or trithelodonts which were contemporaries of at least the Dinosaur Park track species. The size, of the Dinosaur Park form is more consistent with the trithelodonts or the largest of the Early Mesozoic mammals. Trithelodonts (*Pachygenelus monus*) have been found in abundance in the earliest Jurassic McCoy Brook Formation of the Fundy basin in Nova Scotia, in strata very close in age to the Towaco Formation (Olsen and others, 1987; Shubin and others, 1991). I favor trithelodonts as the makers of the Riker Hill species of *Ameghinichnus*, although I cannot exclude other therapsids, including mammals on the basis of existing evidence.

Tens of thousands of footprints have been found in the Early Jurassic age strata of eastern North America. Over 20,000 tracks are in the collection at the Pratt Museum alone (Hitchcock, 1865). It is therefore remarkable that *Ameghinichnus* has been found only in the Towaco Formation at Riker Hill, and then only in the upper part of unit 5. *Rhynchosauroides* sp. (see below) is another track genus known in the Towaco only from its uppermost beds. It may be that the composition of the footprint assemblage follows the expression of the climatic cyclicity, and this portion of a climate cycle is rarely sampled. The uppermost Towaco Formation represents a wetter portion of a poorly expressed Van Houten cycle in the dry phase of a ~100,000 yr short modulating cycle, itself in a drying phase of a ~400,000 yr McLaughlin cycle (Fig. 5). Whatever the explanation, the apparent absence of *Ameghinichnus* from the rest of the Newark Supergroup is very odd.

### Reptilia (true reptiles)
### Lepidosauria (lizards, snakes, sphenodonts, and kin)
### Ichnogenus *Rhynchosauroides*
### *Rhynchosauroides* n. sp.

A single trackway found by John Colegrande in the uppermost Towaco Formation in Towaco, NJ represents the sole known post-Passaic Formation occurrence of *Rhynchosauroides* in the Newark Supergroup (Fig. 9). It is described here because it probably occurs at the Dinosaur Park. This consistently quadrupedal ichnogenus is characterized by a manus impression that is distinctly smaller than the pes, a manus and pes in which digit IV is the longest digit, digit V projects laterally, and there is a phalangeal formula of 2, 3, 4, 5, 3 . Among Newark Supergroup examples, the Towaco *Rhynchosauroides* is distinguished by having very elongate digits with coarse plantar scales and a proportionally smaller manus. A similar form occur in abundance in the uppermost Passaic Formation of very earliest Jurassic age.

The inferred skeletal proportions of the manus and pes and the phalangeal formula of *Rhynchosauroides* is seen in many amniote groups, including very primitive members of the Synapsida. However, by the Triassic period, all of the members of the Synapsida with this primitive phalangeal formula were extinct, and the Towaco form, in fact all Newark *Rhynchosauroides* must have been made by a member of the Reptilia. During the Triassic, there were a very wide range of reptiles that could have made *Rhynchosauroides*-type footprints including the Trilophosauria, Rhynchosauria, Protorosauria, and the Lepidosauria, and in Triassic deposits, *Rhynchosauroides* is not surprisingly the most common footprint form. As far as we know, however, by the Early Jurassic only the Lepidosauria remained. The Lepidosauria include the Rhynchocephalia or Sphenodontia (which includes the living Tuatara) and the Squamata (lizards and snakes). Small members of either group could have made these Jurassic *Rhynchosauroides*.

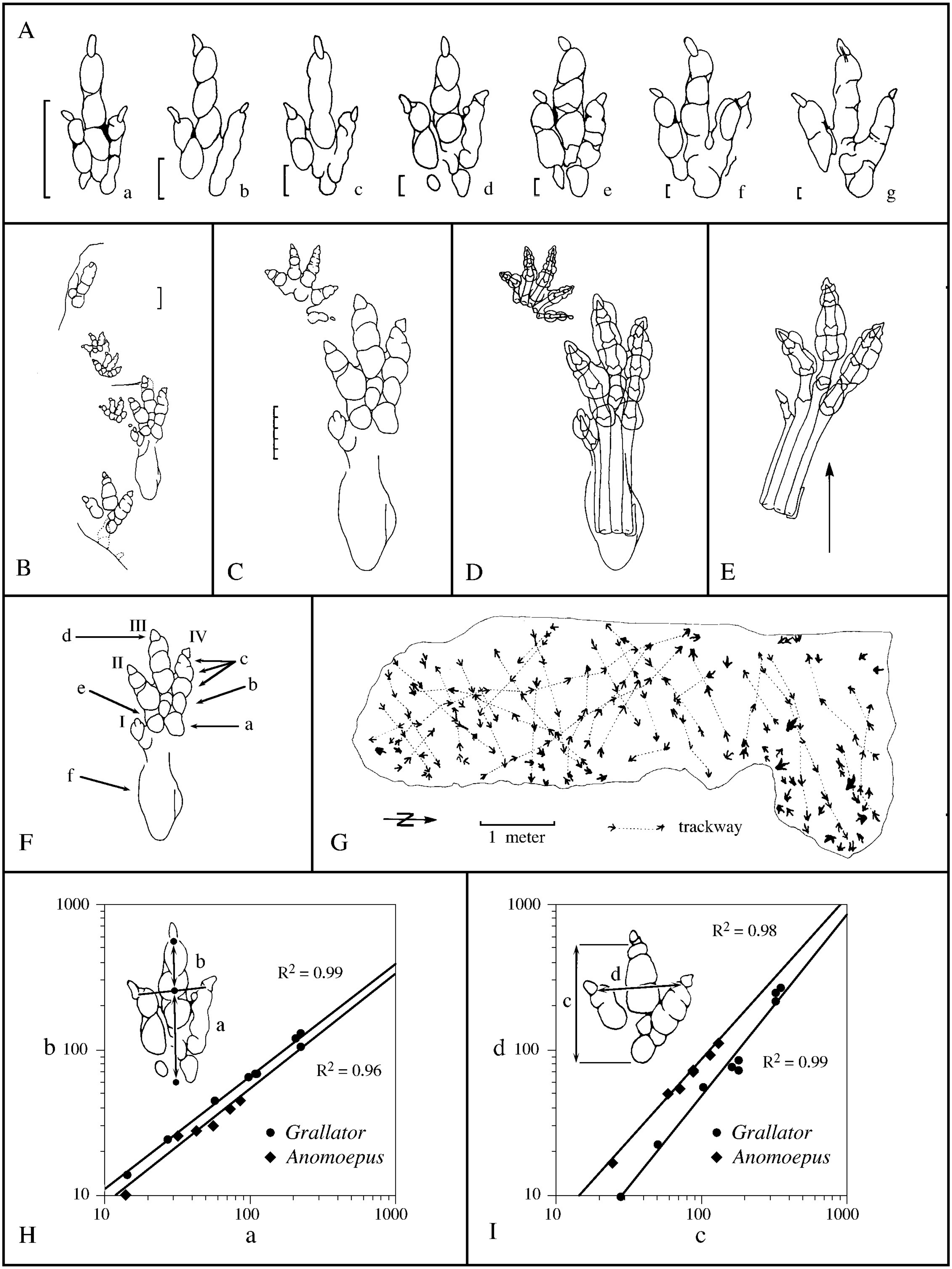
### Archosauria (ruling reptiles, including birds)
### Suchia (crocodiles and their extinct kin)
### Crocodylomorpha (true crocodiles and nearest relatives)
### Ichnogenus *Batrachopus*
### *Batrachopus* sp.

*Batrachopus* was named by Edward Hitchcock in 1845 on the basis of a trackway from the East Berlin Formation of Massachusetts (Olsen and Padian, 1986) (Fig. 9). The form genus is diagnosed as a small quadrupedal form with a five toed manus and a functionally four toed, digitigrade pes. The manus is usually rotated outward so that digit II points forward, digit IV points laterally, and digit V points posteriorly. Digit V of the pes, when impressed, is reduced to a small oval pad. Digit II of the pes is the longest and digit I is the shortest. The inferred phalangeal formula for the pes is 2, 3, 4, 4, 0 and for the manus 2, 3, 4, 4, 3. Digit V of the manus appears to lack a claw (Fig. 9H). In addition to the above cited characters, *Batrachopus deweyi* has a manus impression about 75% of the length of the pes, pedal digits IV and II of similar in length, and pes in which the distal phalangeal pad of digit I is about opposite the crease between the two most proximal phalangeal pads of digit 2.

Although Olsen and Padian (1985) recognized three species of *Batrachopus* (reduced from 15 genera and 31 Newark Supergroup species of previous authors), I believe that perhaps only *Batrachopus deweyi* is valid. The other two species (*B. parvum* and *B. dispar*) are based on inadequate material. It must be noted, however, that he manus impressions of the Roseland forms are much more clear than those of almost any of the types of the various species of *Batrachopus* from the Connecticut Valley. Skin impressions are present on several of the Dinosaur Park specimens (Fig. 9) and the basic form of the manus of those forms is therefore assured. It will be necessary to reexamine all of the Connecticut Valley forms in light of this new material and it seems possible that more than one species will ultimately be recognized.

*Batrachopus* is the most common quadrupedal ichnite in the Newark Supergroup Jurassic, and is sometimes the most common footprint type present. The extreme reduction of digit V is seen in a number of advanced archosauromorphs, but the additional reduction of the primitive number of phalanges in digit IV of the pes to 4 is seen only in the Crocodylomorpha and, in fact, for certain only in the Crocodylia (Olsen and Padian, 1986). Thus, it appears fairly certain that the trackmaker of *Batrachopus* was a primitive crocodilian or perhaps a "paracrocodilian". Skeletal examples of crocodilians have been found in the Early Jurassic Portland Formation of Massachusetts (*Stegomosuchus longipes* - Walker, 1968) and the McCoy Brook Formation of Nova Scotia (*Protosuchus*, Olsen and others, 1987)..

The crocodilians of the earliest Jurassic, such as *Protosuchus*, were rather different in their overall appearance from living crocodiles and alligators. They were small, slender, short snouted, and lightly armored, with no obvious aquatic adaptations. Their skeletons have elongate limbs, which based on *Batrachopus*, appear to have carried the body in a high walk, with the legs more or less under the body. Similarly, they walked digitigrade most of the time, while modern crocodilians walk plantigrade nearly all the time. In contrast of the large lunging semi-aquatic modern crocodilians, the track makers of *Batrachopus* indicate a small, fully terrestrial, active fast type of predator. While I presently recognize only one ichnospecies of *Batrachopus*, (*B. deweyi*) the inferred manus and pes structure is generalized and thus several, if not many biological species might be represented by this one ichnospecies.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R$^2$ = 0.99
R$^2$ = 0.96
● Grallator
◆ Anomoepus
I
1000
d 100
10
10
100
1000
c
c
d
R$^2$ = 0.98
R$^2$ = 0.99
● Grallator
◆ Anomoepus

### Ornithodira (dinosaurs, birds, and pterosaurs)
### Dinosauria (dinosaurs)
### Saurischia ("lizard-hipped" dinosaurs and birds)
### Theropoda (carnivorous dinosaurs) *incertae sedis*
### Ichnogenera *Grallator*, *Anchisauripus*, *Eubrontes*

By far the most abundant dinosaur tracks at the Riker Hill quarry are bipedal, three toed types (Figs. 10, 11) that never have manus impressions. The smallest ones (1.5-15 cm) tend to be very narrow with a distinctly elongate middle digit (III) and the largest ones (20-30 cm) tend to be broad with a relatively short digit III. Only very rarely is there an imprint of the tip of digit I (the hallux). The in between sized forms are intermediate in proportions. The inferred pedal phalangeal formula is ?, 3, 4, 5, ?. These types of tracks have been traditionally called: *Grallator* (Hitchcock, 1858), for the little ones; *Anchisauripus* (Lull, 1904), for the intermediate sized forms; and *Eubrontes* (Hitchcock, 18545), for the largest forms. The phalangeal formula and general proportions are consistent with small to medium sized theropod dinosaurs. Remains of small theropods have been found in the Newark Jurassic deposits in the Portland Formation of Connecticut and Massachusetts and the McCoy Brook Formation of Nova Scotia (Talbot, 1911; Colbert and Baird, 1958; Olsen and others, 1987; Sues and others, 1987). One would think that because they are very common, they must be well known and understood; instead, they present a real nomenclatural mess.

This mess has two origins. First, the history of the nomenclature is sloppy and in desperate need of revision. Most of what are proffered in the literature as type specimens are not, and virtually every named taxon has a tortured and confused history. Second, organisms change in shape as they grow. This is known as allometry and is caused by different growth rates in different parts of the body, and I have argued that much of the variation in shape in these footprints can be explained by growth alone.

For over 90 years the standard references for Newark Supergroup tracks of Early Jurassic age have been the works of Lull (1904, 1915, 1953) As defined by Lull's concept of their type species, the footprint genera *Grallator*, *Anchisauripus* , and *Eubrontes* , apart from size, the major differences between the genera are due to four factors (Fig. 10, 24): 1, size; 2, ratio of length to width; 3, relative projection and length of digit III; and 4, angle of divarication between digits II and 4. When considering the type specimens alone (as listed by Lull, 1953) the genera

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Figure 10. Dinosaurian footprints from the Towaco Formation. **A**, Theropod dinosaur footprints arranged in order of increasing size (from Olsen, 1980c) (scale, 2 cm) - all drawn as right impressions: a-c, Grallator (*Grallator*) spp.; d-f, Grallator(*Anchisauripus*) spp.; g, *Grallator* (*Eubrontes*) *giganteus*.. Locality and disposition of specimens is: a, upper part of unit 18, Walter Kidde Dinosaur Park, John Colegrande collector, John Colegrande collection; b, c, d, g, Vreeland Quarry, Towaco, NJ, Rutgers University Geology Museum main display slab; e, f, lost specimens, Essex County Department of Parks and Recreation collection. **B**, Type specimen (right manus and pes) of the ornithischian dinosaur track *Anomoepus crassus* (Vreeland Quarry, Towaco, NJ, Rutgers University Geology Museum main display slab) which is probably synonymous with *Anomoepus scambus*, the type species of the genus. In this trackway, the dinosaur has sat down, placing its entire ankle on the ground and patted the ground several times with its fore feet. Note the substantial differences in proportions and orientation of the pes of the same individual when walking and when sitting. **C**, Composite of right sitting tracks of *Anomoepus* based on Towaco Formation examples (from Olsen and Baird, 1986). **D**, Reconstruction of right manus and pes skeleton of sitting *Anomoepus* following the rules of Peabody (1948) and Baird (1957). **E**, Reconstruction of right pes skeleton of *Anomoepus* skeleton while walking. For the skeletons to agree in sitting and walking the metatarsal axis must have been held oblique to the direction the digit III pointed and walking direction (arrow). **F**, Basic terms used in describing footprint morphology (right pes shown): I-IV, designations of the digits; a, metatarsal-phalangeal pad of digit IV; b, proximal phalangeal pad of digit IV; c, more distal phalangeal pads, d, ungual impression of digit III; e, crease between metatarsal phalangeal pad and proximal phalangeal pad of digit II; f, impression of metatarsus. **G**, Large slab of *Grallator* footprints from unit 21b, excavated in March, 1977, Riker Hill quarry (see Fig. 11M-N). **H**, Relationship between projection of digit III (b) and length of rear of pes (a) in the footprints shown in figures 11-13; note that the proportions of *Grallator* and *Anomoepus* are consistently different and that all the individuals of each genus lie on the same line (dimensions are in mm). **I**, Relationship between length (d) and width (d) of pes of *Grallator* and *Anomoepus* (dimensions are in mm); again, all specimens of each genus fall on the same line.

appear morphologically quite distinct. However, when we attempt to place other specimens in these taxa we find that there are a multitude of intermediate forms. This problem was apparent to Edward Hitchcock who, along with his son (C. H. Hitchcock) erected dozens of species for these intermediates which through time were moved in and out of these and other genera and many species in a vain attempt to bring order to the array of morphologies. These practices were continued and reified by Lull. If we look into the sample of footprints from Riker Hill quarry (Figs. 10, 11), some tracks fall close to Lull's concept of *Grallator*, some to *Anchisauripus*, and some to *Eubrontes*. Others appear similar to various named species referred to these three genera, while others still seem to be as different from any of the figured species as they do from each other. However, for the names we apply to have any significance at all, they must be objectively definable.

The relationship between the four main factors that differentiate Lull's concept of the type species is displayed graphically in figure 10H and I, along with data from all of the available Riker Hill specimens available to me at the time of writing. As suggested by Olsen (1980) all of the forms lie on one morphological trend varying in a consistent way with size. From these graphs, it is not at all apparent to me that it is possible to objectively isolate portions of this trend as separate taxa. Expressed in words, as the size of the footprint increases, the relative width of the footprint increases along with the divarication angle of digits II and IV and a relative decrease in the projection of digit III and its relative length. Some of these relations were suggested by Lull (1953) in his use of deformed Cartesian plots, where he attributed some of the proportional changes due to the greater weight of larger animals.

From these graphs, it is possible to conclude that we might recognize only one species of footprint to encompass the entire range of variation along a growth trajectory. It seems more likely to me, however, that several different species of dinosaurs made these tracks, each with feet with shapes in more or less in accord with their size. The same general proportional changes can be seen in the skeletons of the small ceratosaurian theropods *Rioarribasaurus* (*Coelophysis*) and the much larger *Dilophosaurus*. The larger specimens of the former fit the proportions of large *Grallator* or small *Anchisauripus*. The very large assemblage of *Rioarribasaurus* (*Coelophysis*) from Ghost Ranch, New Mexico (Colbert, 1989) might represent a population large enough to see what kind of change in shape with increasing size actually occurs within a single dinosaurian species.

If these footprints cannot be objectively split up into several genera, they should all be given the earliest proposed valid name. Pending a revision of these genera, I have been tentatively referring to them all as *Grallator* spp. because that seems to be the earliest valid name given to a track that has well preserved pads (Hitchcock, 1858). *Eubrontes* would seem of be earlier (Hitchcock, 1845), but there is considerable confusion about what specimen is the type. Therefore, I have recognized the informal subdivisions *Grallator* (*Grallator*) spp., *Grallator* (*Anchisauripus*) spp., and *Grallator* (*Eubrontes*) spp. (Figs. 10, 11).

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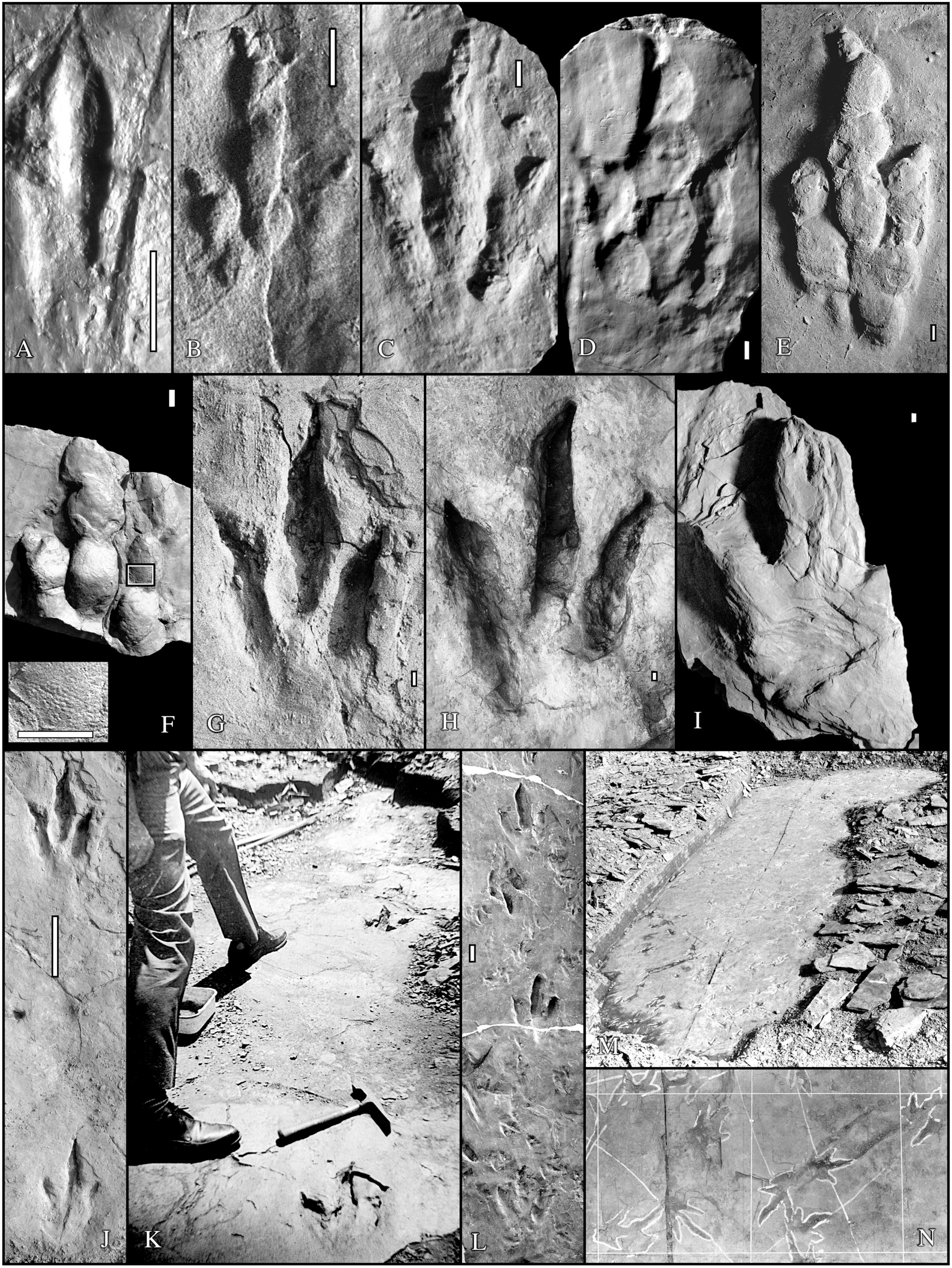
Figure 11. Theropod dinosaur footprints from the Towaco Formation (mostly of the Riker Hill quarry). **A**, Natural cast of left pes of very small, Grallator (*Grallator*) sp., upper unit 18, Walter Kidde Dinosaur Park, John Colegrande collector, John Colegrande collection (same as figure 10Aa and same slab as figure 13C). **B**, Natural cast of left pes of *Grallator* (*Grallator*) sp., Riker Hill Quarry, ECPC 21; **C**, *Grallator* (*Anchisauripus*) sp., Riker Hill Quarry (Robert Salkin collector, Robert Salkin collection). **D**, Right pes of Grallator (*Anchisauripus*) sp., plaster cast of specimen, Riker Hill Quarry, AMNH 29299. **E**, Natural cast of left pes of *Grallator* (*Anchisauripus*) sp., upper unit 18, Walter Kidde Dinosaur Park, lost specimen. **F**, Natural cast of right pes of *Grallator* (*Anchisauripus*) sp., same trackway as E (above); note scale impressions in inset (specimen lost). **G**, Left pes of *Grallator* (*Anchisauripus*) sp., upper unit 18, Dinosaur Park, specimen not collected; same track as second in trackway in J (below). **H**, Left pes of *Grallator* (*Anchisauripus*) sp., upper unit 18, Dinosaur Park, specimen lost; same track as first in K (below). Scale for A-I is 1 cm. **I**, Partial natural cast of *Grallator* (*Eubrontes*) *giganteus* , upper unit 18, Dinosaur Park, specimen lost. **J**, *In situ* trackway of *Grallator* (*Anchisauripus*) sp., upper unit 18, Dinosaur Park, specimens not collected). **K**, *In situ* trackway of *Grallator* (*Anchisauripus*) sp., upper unit 18, Dinosaur Park, second track in series is ECPC 9. **L**, Trackway of *Grallator* (*Eubrontes*) *giganteus* and many other footprints, Vreeland Quarry, Towaco, NJ, Rutgers University Geology Museum main display slab. **M**, In situ *Grallator* footprint bearing layer of unit 23c, Riker Hill quarry (see fig 10G). **N**, *Grallator* footprints on surface of unit 23c from slab shown in M (above).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Among the many *Grallator* tracks from Riker Hill are some very small examples (Fig. 11, 13). These tracks are among the smallest dinosaur footprints known anywhere.

### Theropoda (carnivorous dinosaurs) *incertae sedis*

The only likely candidate for a dinosaur body fossil from the Riker Hill quarry is a 2.5 cm shard of a large blade-like tooth found in the upper part of unit 18. Other than theropod dinosaurs no other Early Jurassic animals were large enough to produce such a fragment. The tooth probably belonged to the makers of the *Grallator* (*Eubrontes*) type tracks. The tooth fragment is all the more unusual because it was found in the natural cast of digit III of a *Grallator* (*Eubrontes*) track itself. The shallow lake shores and mudflats on which the dinosaurs trod had little preservation potential for bones, and the hole created by the dinosaur track provided a place to catch the tooth fragment.

### Ornithischia ("bird-hipped dinosaurs) *incertae sedis*
### Ichnogenus *Anomoepus*
### *Anomoepus scambus*

The ichnogenus *Anomoepus* (Hitchcock 1848) is the only other major dinosaurian track form that has been definitely recognized from the strata of the Riker Hill quarry (Figs. 10-13). The trace fossil genus is distinguished in bipedal walking tracks by having the metatarsal-phalangeal pad of digit IV nearly in line with digit III, having a short digit III for the size of the foot, and more divaricate pedal digits. Sitting traces are fairly common, in which the entire pes, including the metatarsus is impressed along with the five-toes manus (Fig. 10, 13). In these sitting traces, the metatarsal-phalangeal pad of digit IV is more laterally placed relative to the projection of digit III, there is usually an impression of digit I, and the angle between digits II and IV is decreased. There are occasionally true quadrupedal walking traces as well.

The wide range of sizes of *Anomoepus* present at Riker Hill well show the range of form of the genus. This variation in form is, however, much less than in seen in the *Grallator* forms described above. I cannot, however, in this range of forms find criteria for recognizing more than one footprint species and therefore refer them all to the type species *Anomoepus scambus*, from the Turners Falls sandstone possibly of Turners Falls, Massachusetts. Also unlike *Grallator*, there seems to be little change in shape with size, except perhaps for a slight relative shortening of digit III with increasing size.

Because *Anomoepus* exhibits both walking and sitting traces, the amount of osteological and functional information that can be gained from the tracks is much greater than in *Grallator*. Most important are the changes in track form seen within a trackway of a single individual as it walks and sits down (Fig. 10). Assuming that the metatarsal-phalangeal pads indeed underlie the joints between the metatarsals and phalanges, the phalanges must be rotated medially relative to

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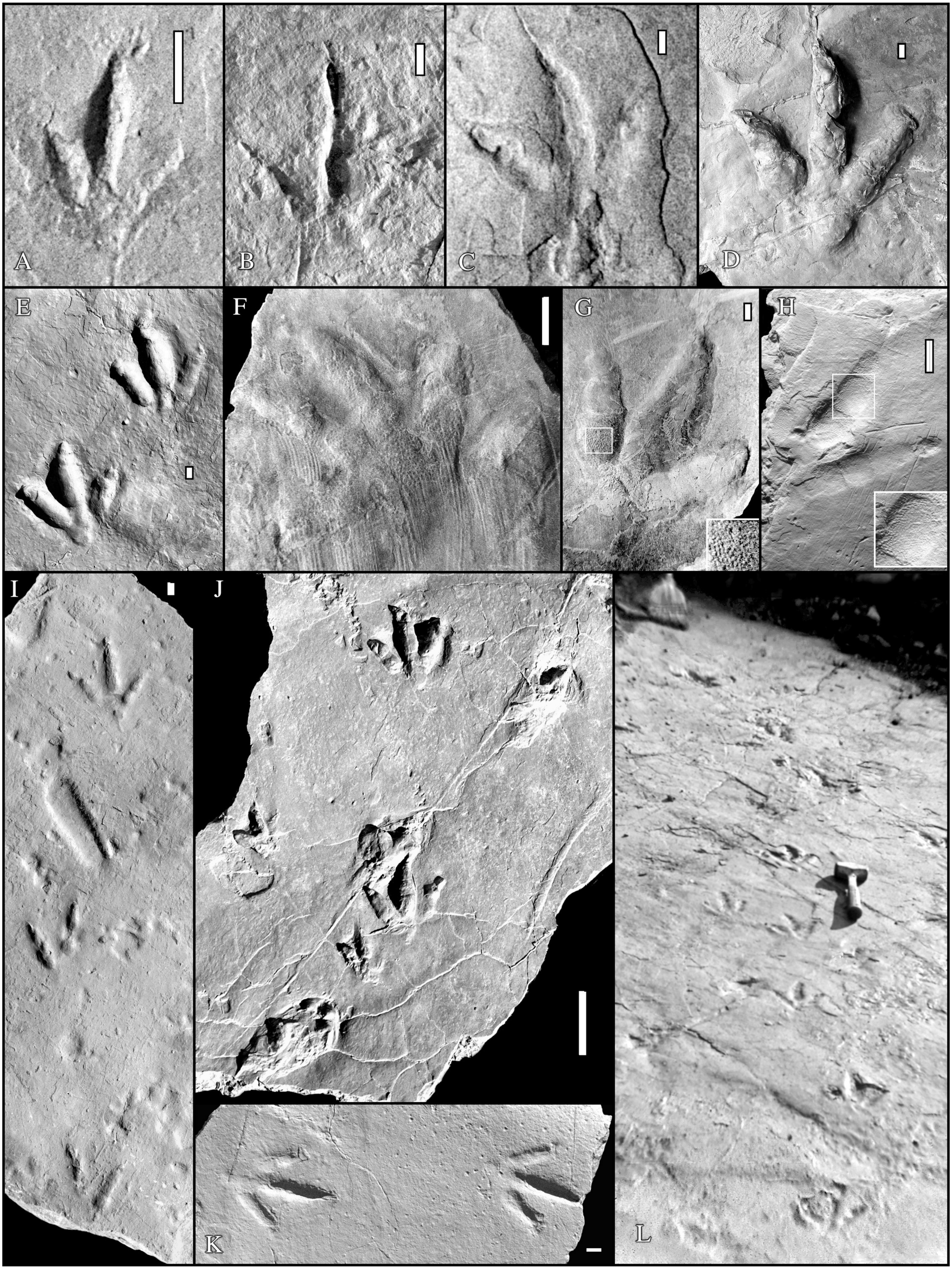
Figure 12. Ornithischian dinosaur footprints (*Anomoepus*) from the Towaco Formation of the Riker Hill quarry). **A**, Natural cast of very small left pes of, upper unit 18, Walter Kidde Dinosaur Park (John Colegrande collector, John Colegrande collection) (same slab as figures 13A). **B**, small right pes, Riker Hill quarry, specimen lost. **C**, Natural cast of small pes upper unit 18, Dinosaur Park, ECPC 38. **D**, Natural cast of large left pes upper unit 18, Dinosaur Park; specimen donated to Copenhagen Museum of Natural History, Copenhagen, Denmark. Same bedding surface as E, J and L. **E**, Natural cast of right and left pedes, upper unit 18, Walter Kidde Dinosaur Park, ECPC 5 (?lost). **F**, Natural cast of right manus with skin impressions. **G**, Natural cast of left pes with skin impressions (see inset). **H**, Right pes with very fine skin impressions (see inset), unit 5, Walter Kidde Dinosaur Park (Charles Rizzo collector, Charles Rizzo collection). Scale for A-H is 1 cm. **I**, Trackway of small individual, upper unit 18, Walter Kidde Dinosaur Park (specimen lost) (scale, 1 cm). **J,** Natural cast of trackways of large and small *Anomoepus* and an indeterminate footprint form, upper unit 18, Walter Kidde Dinosaur Park, uncatalogued AMNH specimen (scale, 10 cm). **K**, Trackway, same slab as figure 11N, Riker Hill quarry, collector and disposition unknown (scale 1 cm). **L,** *In situ* trackways, mostly of *Anomoepus*. Impressions of E (above) are just to left of hammer; and impressions of tracks in J (above) are above and to the left of hammer (hammer is about 1 ft long).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the metatarsus in order to have the metatarsal-phalangeal pad of digit IV be in line with the projection of digit III (Fig. 10). When siting, the pes must have been rotated outward relative to the metatarsus to get the normal dinosaurian configuration seen in the sitting tracks. Thus when sitting, the pes has a shape similar to the much larger *Grallator* (*Eubrontes*) *giganteus*.

The structure of the inferred pedal skeleton could be compatible with either a theropod or an ornithischian. The hand however, flatly rules out a theropod because all five digits remain well developed, although short. Even the most primitive probable theropod *Herrerasaurus* has a vestigial digit IV, and digits I, II, and III are all very long compared to digit IV. In other theropods, digit V is lost and digit IV is vestigial. Also digits I, II, and III bear large trenchant claws in the non-bird theropods. In contrast to theropods, manual digits II, III, and IV are dominant in *Anomoepus*, which is the beginnings of a trend seen in more advanced ornithischians in which the lateral digits are reduced and finally lost (as in hadrosaurs). *Anomoepus* was therefore probably made by a herbivorous, small relatively primitive ornithischian dinosaur similar to *Lesothosaurus* or some other so called "fabrosaur". Scrappy bones and isolated teeth of "fabrosaurs" have been found in the McCoy Brook Formation of Nova Scotia (Olsen and others, 1987; Sues and others, 1987).

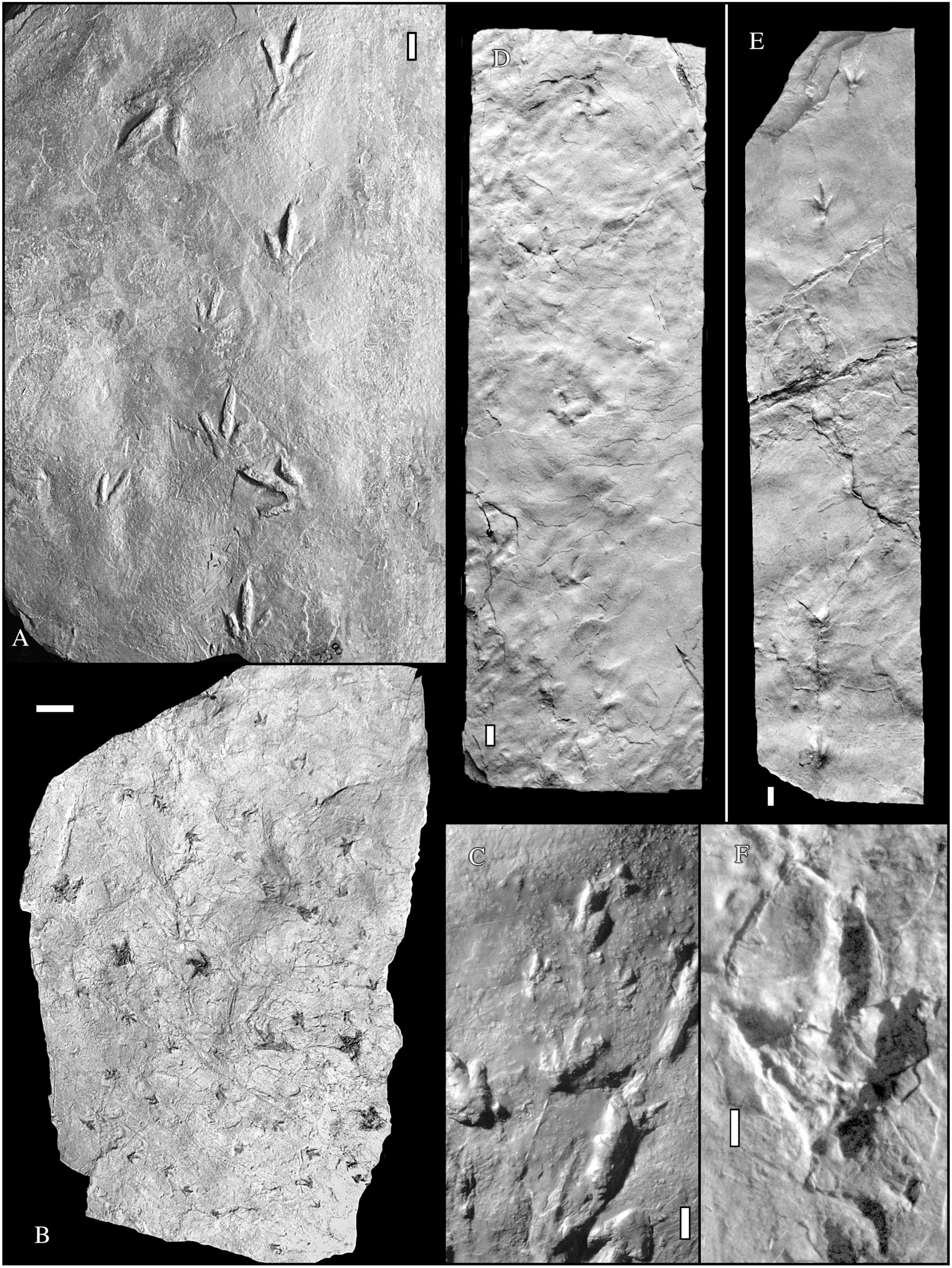
*Anomoepus* is characterized by a less well developed pad structure in the pes than *Grallator*. Although the skin texture (Figs. 10, 12) is very similar to *Grallator*, the pads tend to be separated by smaller narrow pads, suggesting some flexing of the foot was common. The pads on the hand show this very well and in fact appear to show creases or grooves over the articulations, which is what would be expected in a hand used more for grasping than walking (Fig. 10-12). Thus, it seems likely that *Anomoepus* used its hands, and sometimes its feet to grasp things, probably branches - a reasonable scenario for a small ornithischian dinosaur.

One of the most unusual aspects of the Riker Hill assemblages is the exceptionally large number of presumably juvenile *Anomoepus* tracks (Fig. 13). One layer in particular in the upper part of unit 18 was covered in many small and a few larger *Anomoepus* (Fig. 13). The association of the uncommon larger forms with the much smaller forms suggests, but of course does not demonstrate herding of young. The smallest *Anomoepus* tracks are, like the tiny *Grallator* in figure 13, among the smallest dinosaur footprints known. Unfortunately, also like the tiny *Grallator*, these tracks lack pads and the assignment to *Anomoepus* is tentative. One of the minute *Grallator* track ways in figure 11 is from the same bedding plain as the abundant baby *Anomoepus*. The meaning of the diminutive carnivore among the baby herbivores is unknown.

### Dinosauria (dinosaurs) *incertae sedis*
### Ichnogenus *Hyphepus* E. Hitchcock 1858
### ?*Hyphepus* sp.

Some not very clear bipedal trackways from Riker Hill closely resemble the ichnogenus *Hyphepus*, originally described by E. Hitchcock in 1858 (Fig. 13). *Hyphepus* is characterized by a *Grallator*-like pes with a pronounced, backward directed digit I impression. It is difficult to reconcile the form of this track with the other two dinosaurian ichnotaxa from the site; however, the footprints, like the type, are not clearly impressed and the apparent structure could be due to a normal *Grallator* -type trackmaker foot interacting with the substrate in a peculiar manner. I

Figure 13. Baby dinosaur tracks and ?*Hyphepus*. **A**, Natural cast of several trackways of very small Anomoepus, upper unit 18, Walter Kidde Dinosaur Park (John Colegrande collector, John Colegrande collection) (same slab as figure 12A) (scale, 1 cm). **B**, Large slab of natural casts of numerous trackways of small individuals and one larger individuals of *Anomoepus* suggestive of herding, upper unit 18, Walter Kidde Dinosaur Park, specimen destroyed (scale, 10 cm). **C**, Sitting tack of very small *Anomoepus*, upper unit 18, Walter Kidde Dinosaur Park (John Colegrande collector, John Colegrande collection) (same slab as figures 11A and 10Aa) (Scale, 1 cm). **D,** Extremely small underprints of *Anomoepus*, Riker Hill quarry (Robert Salkin collection) (Scale, 1 cm). E, Extremely small undertracks of *Grallator*, Riker Hill quarry (Robert Salkin collection) (Scale, 1 cm). **F,** Possible Hyphepus sp., Riker Hill quarry (Robert Salkin collector, Robert Salkin collection).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doubt the validity of this taxon, but include it here in case impressions showing clear pads are discovered.

## PALEOENVIRONMENTS AND PALEOECOLOGY

The rich fossil assemblages from former Riker Hill quarry and the present Dinosaur Park fit into a context of cyclically and periodically changing environments. The sedimentary cyclicity produced by orbitally controlled lake level changes was the result of a laterally shifting array of environments.

At lake high stand, during the deposition of division 2 of cycles RVH 2 and 3 (units 28, 23, and 13), the lake was probably in excess of 50 m deep, perhaps more than 100 m (Olsen, 1988). The shorelines lapped against the edges of the basin: a steep fault scarp and small fan deltas on the northwest and a gentle delta plain on the east and southeast. The highlands were cloaked in forests of cheirolepidaceous conifers along with an understory of cycadophytes and ferns. Forest litter and insects were washed into the lake occasionally. The lake phytoplankton differed markedly from most modern lakes because the dominant forms of today, diatoms, had not yet evolved (Olsen, 1988). Chlorophyta (notably the micro-green algae) and Cyanobacteria (blue-green "algae") were probably the dominant phytoplankton instead. The shallows of the lakes were teeming with dozens (if not hundreds) of species of *Semionotus*, many of which evolved as the lake level erratically rose. The few riverine species of *Semionotus* that colonized the Newark Jurassic lakes found themselves pretty much alone in a giant open environment. They quickly evolved to fill the ecological voids. They fed on debris from the land, as yet unknown zooplankton and benthic invertebrates, algal bioherms along the lake edge, and each other. The water column in the deeper parts of the lake was chemically stratified, with anoxic depths. The lack of oxygen excluded bioturbating and scavenging organisms, and any fish that sank into those depths were preserved in the microlaminated sediments (Fig. 7).

As the lake dried up, following the ~20,000 yr cycle of climatic precession, it formed occasionally flooded playas and ponds of the lake low stand. Most *Semionotus* species became extinct. Large areas of mud flats were exposed as small scale lake level changes produced large lateral shifts of the shoreline on the nearly flat basin floor. Small, gracile crocodyliomorphs and small to medium sized theropod dinosaurs walked along the waters edge looking for unwary prey. Groups of baby and adult ornithischian dinosaurs milled about when most of the theropods and larger crocodilians were elsewhere, feeding on scrubby plots of cheirolepidaceous conifers. During cycle RVH-4, the archosaurian assemblage was joined by small advanced synapsids or mammals and lizards or sphenodontians.

The types of footprints seen at the Dinosaur Park comprise a Connecticut Valley-type assemblage (e.g., Lull, 1953), typical of Early Jurassic age deposits world-wide. Fine examples outside eastern North America include assemblages from the Wingate, Moenave and Kayenta formations of the southwestern United States (Lockley and Hunt, 1995), the so called Infralias of France (Lapparent and Montenat, 1967), the Holy Cross Mountains in Poland (Gierlinski, 1991), and the Stormberg Group of southern Africa (Ellenberger, 1972, 1974; Olsen and Galton, 1984).

In comparison with Triassic age assemblages, the plant and vertebrate assemblages the Early Jurassic, as seen at the Dinosaur Park, were of low diversity. Some 400,000 years earlier, diverse terrestrial communities of the Triassic were evidently wiped out in the largest of the two great Mesozoic extinction events - the Triassic-Jurassic mass extinction. Based largely on studies in the Newark basin, the transition from a rich Triassic plant and animal community to that of the Jurassic took much less than 20,000 years (a single Van Houten cycle), the record of the change being preserved within a few tens of meters of the base of the Orange Mountain basalt (Olsen and others, 1995). A massive increase in fern spores marks the floral transition, which itself takes place over an interval of less than a few meters (Fowell and Olsen, 1993; Fowell and others, 1994). A similar pattern of vertebrate footprint last appearances occur just below the floral transition (Olsen and others, 1990; Silvestri and Szajna, 1993; Szajna and Hartline, 1995). The pattern at the local and global level is very similar to the second greatest mass extinction of the

Mesozoic - the Cretaceous-Tertiary mass extinction (Olsen and others, 1987). The evidence for a massive asteroid or comet impact at the Cretaceous-Tertiary boundary is now overwhelming and the implications for dinosaurian extinction seems clear (see Benton and Little, 1994 for a brief review and papers in Silver and Schultz, 1982; Sharpton and Ward, 1990; and Anonymous, 1994). Although no iridium anomaly has been found at any Triassic-Jurassic section, shocked quartz has been found at the boundary at two localities (Badjukov and others, 1987; Bice and others, 1992) and a search for it is underway at Newark Supergroup localities. The shocked quartz is *prima facie* evidence for a giant asteroid or comet impact. Thus, the faunal and floral assemblages at the Riker Hill Quarry are in my view recovering in evolutionary-time from a global catastrophe, and bear witness to that mass extinction by their low generic and familial taxonomic diversity. However, ~400,000 years is long enough for considerable species level evolution (as seen in *Semionotus*) and it may be that the terrestrial fauna and flora had already recovered significant species diversity. Unfortunately, that diversity may be invisible in the largely trace fossil record preserved in the Towaco Formation.

## CONCLUSIONS

Strata formerly exposed in the Riker Hill Quarry and presently exposed in the Walter Kidde Dinosaur Park consist of sedimentary cycles produced by the rise and fall of very large lakes under the control of astronomically induced climate change. These cycles contain an aquatic assemblage of molecular fossils of phytoplankton and bacteria and body fossils of fishes, and terrestrial assemblages composed of plants and the extraordinary tetrapod footprints the site is famous for. The overall importance of the Dinosaur Park, however, lies not only in its extraordinarily preserved footprint assemblages, not only in its educational value as an example of local geology, paleontology, and climate change, but also as part of the record of the biotic recovery from the Triassic-Jurassic mass-extinction, one of the largest catastrophes in Earth history.

## ACKNOWLEDGMENTS

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