The "Age of Dinosaurs" in the Newark Basin, with Special Reference to the Lower Hudson Valley

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ABSTRACT

This field guide is intended as an introduction to the rich stratigraphic and paleontological record of the Triassic-Jurassic Newark rift basin, especially in the vicinity of the present and ancestral routes of the lower Hudson River. We will visit seven stops that illustrate this region's range of sedimentary and igneous environments and paleobiological assemblages, focusing on their significance to the understanding of global events in the early Mesozoic, in particular the beginning of the "Age of Dinosaurs".

INTRODUCTION

The Newark basin (Figure 1) is one in a remarkable series of early Mesozoic rift basins that extend from Greenland to Europe, Morocco and eastern North America, and to the Gulf of Mexico, comprising the largest known rift system. This massive set of basins - the central Atlantic margin rifts - formed during the crustal extension that led to the fragmentation of Pangea (Figure 1). The Newark basin is one of the largest segments of the outcropping, deeply eroded North American contingent of these rifts, the basin fill of which is collectively termed the Newark Supergroup (Figure 1). Continental rifting seems to have begun in eastern North America sometime in the median Permian and finished in the Early Jurassic, although the exact timing of the termination of rifting is poorly constrained. These rifts - in particular the Newark basin - also record a major tectonic paroxysm that punctuated the beginning of the Jurassic: the emplacement of basaltic intrusions and extrusions of the Central Atlantic Magmatic Province (CAMP) (Marzoli, 1999; Olsen, 1999) - the largest known igneous province (Figure 2).

A "Hot House" mode of global climate system apparently prevailed during the Triassic and Early Jurassic, with little or no convincing evidence of ice at the poles, probably due to very elevated CO_2 levels (Ekart and Cerling, 1999; Tanner and Hubert, 2001). Despite the profound difference between today's global climate and that of the early Mesozoic, tropical climate gradients, as reflected by indicators of humidity, were evidently not much different than today – and hence quite strong (Kent and Olsen, 2000). During this time, Pangea straddled the equator, its central region drifting slowly northward through time (Figure 2). The Newark basin lay in this central region, and drifted from an equatorial position in the late Middle Triassic or earliest Late Triassic (~232 Ma) to about 7˚N by the beginning of the Jurassic (~202 Ma). As a consequence, the Newark basin itself slowly drifted from the wet tropics through a strong climate gradient towards the arid climate belt, producing a sedimentological transition that is well displayed in the basin sediments.

Within this context of the Early Mesozoic "Hot House" world, climate was far from stable in the tropics. As is true for tropical climate during the Quaternary, that of the

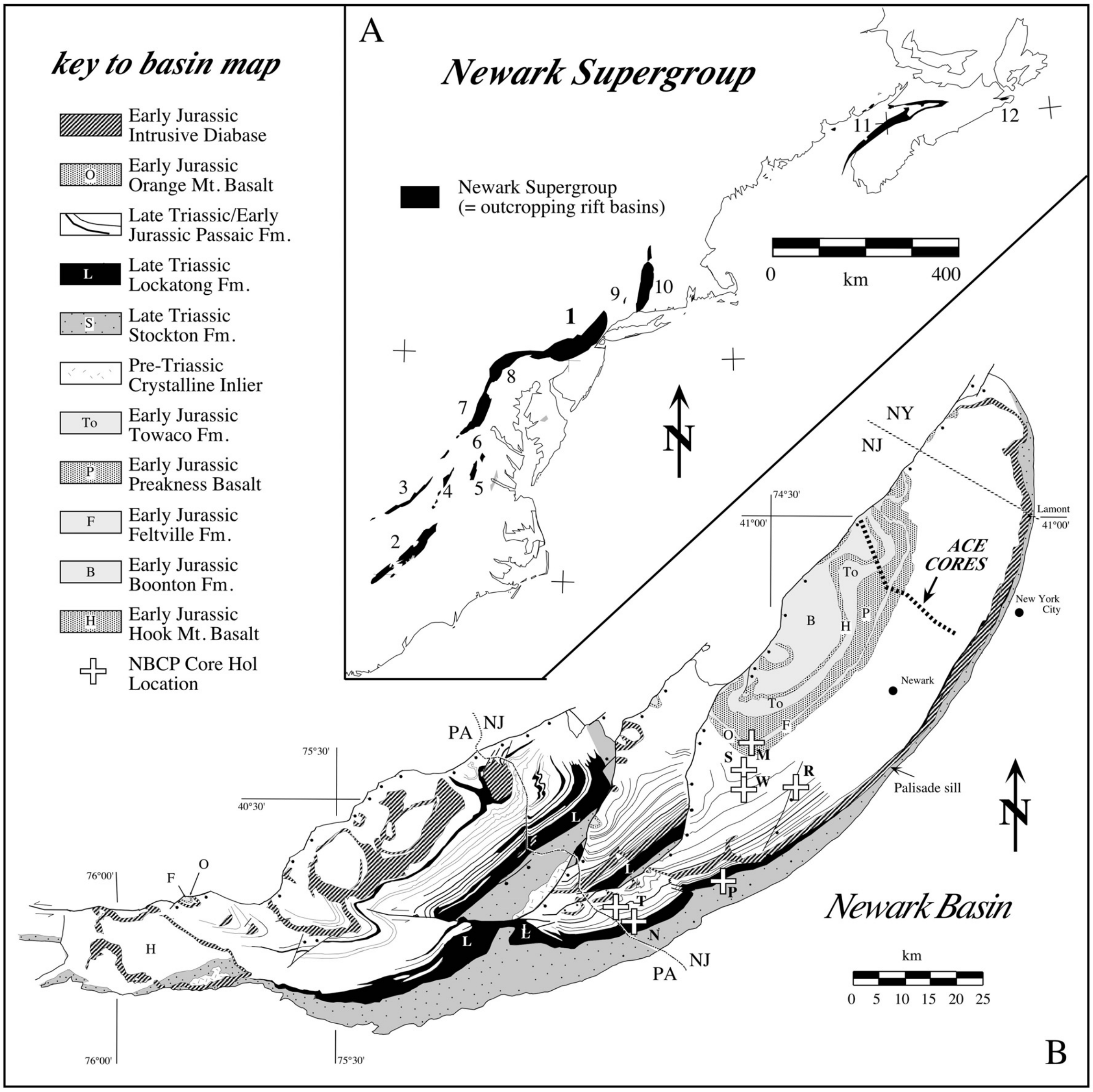

Figure 1. Central Pangean rift basins in the Early Jurassic Pangea relationship to the CAMP. **A**, rift basins of central Pangea showing the position of the Newark basin, the Long Island Platform - South Atlas fault zone (LIP-SAF) and the Minas - Gibraltar fault zone (MFZ-GFZ) (modified from Olsen, 1997). B, Pangea in the Early Jurassic showing the spatial relationship between the CAMP and the central Pangean rift zone (modified from Olsen et al., 2002a).

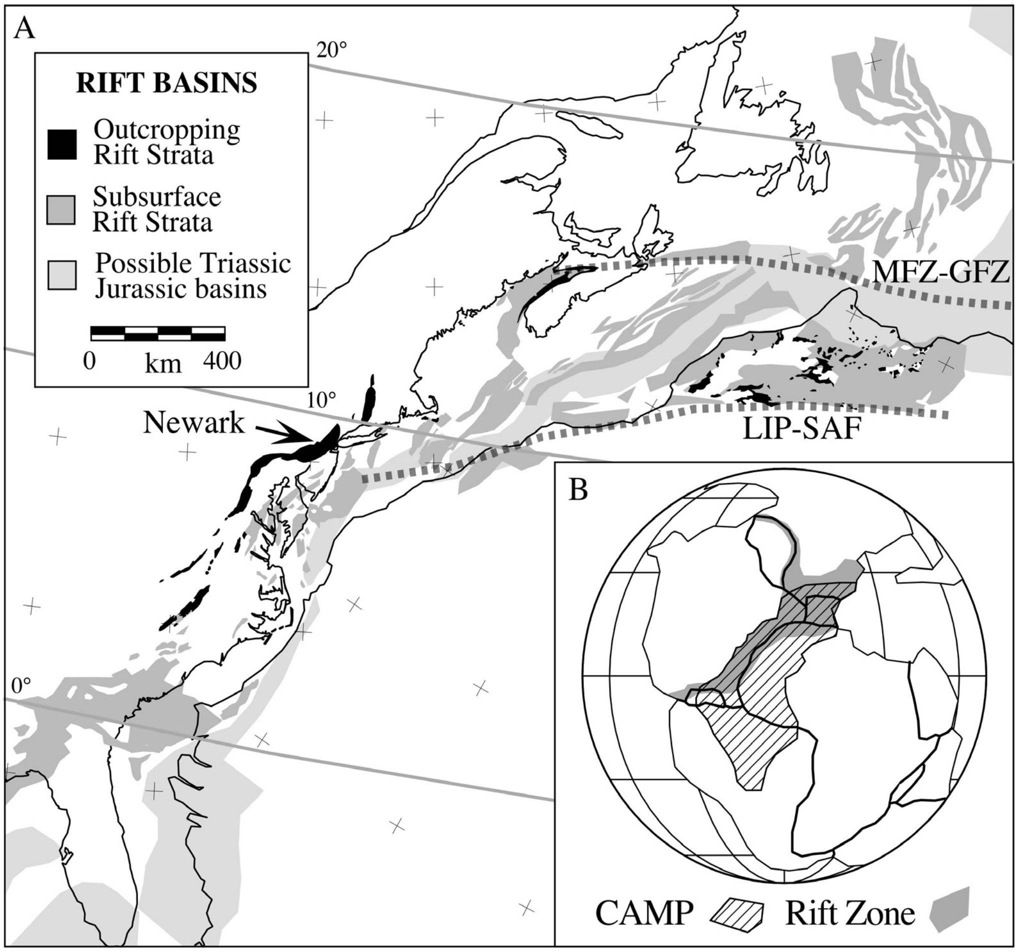

Figure 2. Newark basin section and time scale showing distribution of field stops (adapted from Olsen and Kent, 1999; Olsen et al., 2001a; Olsen et al., 2002b).

Triassic and Early Jurassic fluctuated dramatically in precipitation following Milankovitch climatic cycles, driven by variations in the Earth's orbit. These precipitation and evaporation cycles are recorded as lake level cycles of several orders of complexity in the abundant Newark Supergroup lacustrine deposits, and especially in the Newark basin (described in more detail below). In addition to providing a constantly fluctuating sedimentary environment sampling various lacustrine to fully terrestrial biological communities, these cycles provide a rigorous 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 were pivotal. The early Mesozoic opened following the largest mass-extinction of all, that of the end-Permian. However, terrestrial communities of the Early Triassic largely inherited the Paleozoic-style dominance of synapsid amniotes (the oxymoronic "mammal-like reptiles"), and very distinct northern and southern hemisphere floras. Through the Triassic, however, diapsid sauropsids (lizards, crocodilians, dinosaurs and their relatives) became progressively more abundant, diverse, and larger, so that by the beginning of the Late Triassic synapsids were rare in tropical regions, except for a narrow belt around the equator. 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, as explored in this fieldtrip guide.

STRATIGRAPHIC ARCHITECTURE, CYCLOSTRATIGRAPHIC FRAMEWORK, AND STRATIGRAPHIC NOMENCLATURE OF THE NEWARK BASIN

Based on extensive scientific and industry coring, drilling, and seismic profiles, and outcrop studies in eastern North America and Morocco, Olsen (1997) recognized four tectonostratigraphic sequences in the central Pangean rifts (Figure 3). Tectonostratigraphic sequences (TS) are similar in concept to marine sequence stratigraphic units in that they are largely unconformity-bound genetically-related packages, but differ from them in that there it is assumed they are controlled largely by tectonic events. Tectonostratigraphic sequence I (TS I) is apparently median Permian in age and is present for certain only in the Fundy basin of maritime Canada and various Moroccan basins; however, it may very well be present in the subsurface in other basins. Tectonostratigraphic sequence II (TS II) is of ?Middle (Anisian-Ladinian) Triassic to early Late Triassic (Early to early Late Carnian) age and is present in most Newark Supergroup basins, dominating the preserved record of some (e.g. Richmond basin). Tectonostratigraphic sequence III (TS III), of early Late Triassic (Late Carnian through early Late Rhaetian) age, is the most widespread of the sequences and dominates nearly all Newark Supergroup basins. Tectonostratigraphic sequence IV (TS IV) is of latest Triassic (Late Rhaetian) to Early Jurassic (Hettangian and Sinemurian) age, and contains the Triassic-Jurassic boundary, extrusive tholeiitic basalts of the CAMP, and occasionally extensive post-CAMP sedimentary strata. At the hingeward edges of the rift basins, the unconformities between the tectonostratigraphic sequences can represent large hiatuses, but may pass into correlative conformities at depth within the basins, with no break in sedimentation. The exception is the TS I – TS II boundary, which, as far as is known, always represents a hiatus of a score or so million years. TS II through IV are present in the Newark basin and represent the fundamental stratigraphic and sedimentological units of the basin sequences, transcending the traditional formational bounds.

Tectonostratigraphic sequences II – IV at least were probably initiated by major pulses of regional extension which subsequently declined, as hypothesized by the basin filling model (outlined by Schlische and Olsen, 1990, and elaborated on by Contreras et al., 1997) (Figure 3). As a consequence of the growth of the accommodation space during the extensional pulse, and disregarding climate changes, the basin depositional environments should follow a tripartite development at their depocenters, consisting of a basal fluvial sequence, succeeded by a rapidly deepening lacustrine sequence, and finally followed by slow upward shallowing. The slowing or cessation of the creation of new accommodation space would cause additional shallowing and thus a return to fluvial conditions; eventually erosion would ensue if creation of accommodation space stopped or nearly stopped. Each new pulse of extension would be expected to produce a shift of

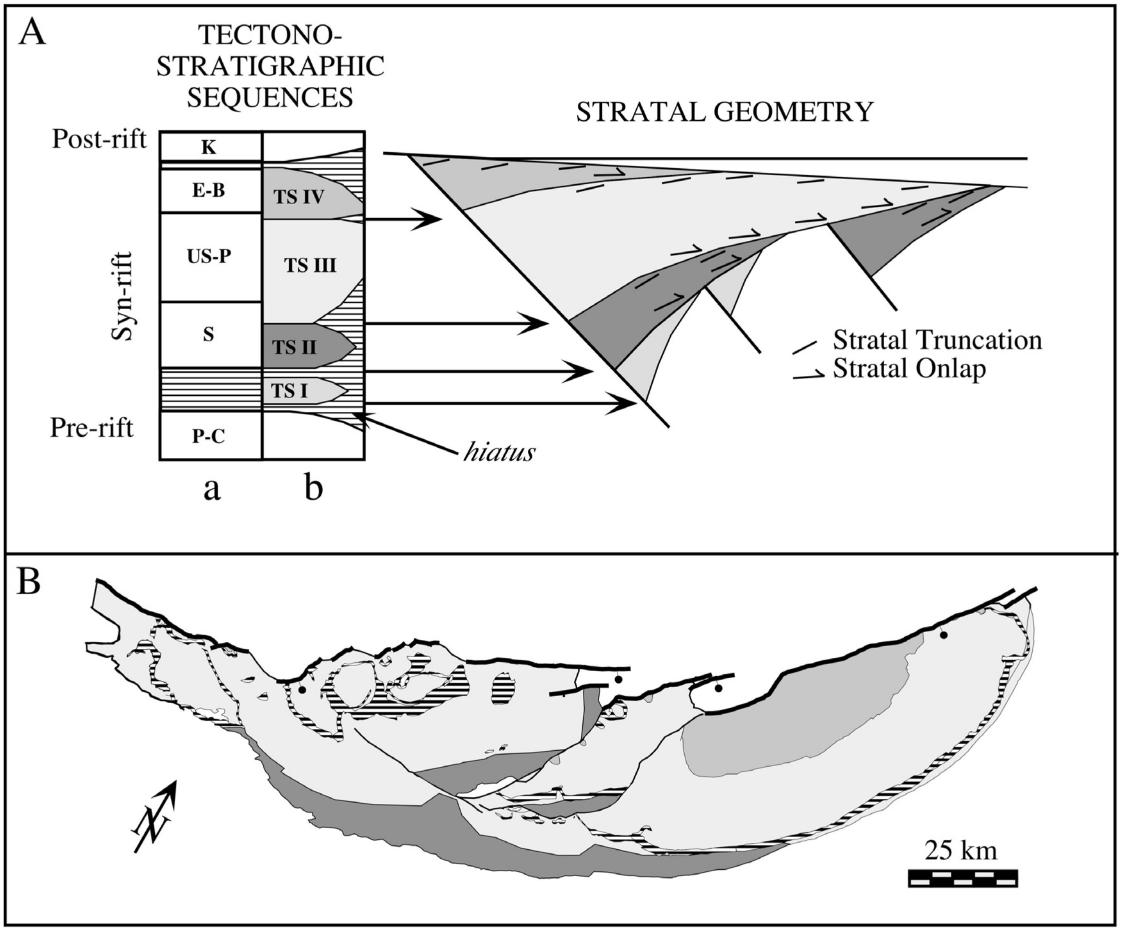

Figure 3. Tectonostratigraphic sequences of the central Pangean rifts and Newark basin. **A**, generalised tectonostratigraphic sequences of central Pangean rifts (modified from Olsen, 1997). **B**, map of the Newark basin showing extent of tectonostratigraphic sequences with the patterns corresponding to **A** above (dark horizontal ruling are intrusive diabase).

the depocenter towards the boundary fault system, accompanied by erosion of the hanging wall deposits; this would continue until the basin fill onlapped those areas of the hanging wall. We hypothesize that the hanging wall unconformities between TS II, III, and IV were each caused by a renewal of extension. This certainly is true of the TS III-IV boundary in the Newark basin, since it is actually a correlative conformity in most presently-outcropping areas. Whether or not the full basin filling sequence - termed a Schlische cycle by LeTourneau (2002) - is actually observed in outcrop, depends on the depth of erosion relative to the basin depocenter and the boundary conditions of the basin geometry and sediment input.

Cyclostratigraphy

As a result of over a century of intensive outcrop work and recent coring, drilling and seismic exploration, the Newark basin 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 (NBCP) (Goldberg et al., 1994; Kent et al., 1995; Olsen and Kent, 1996; Olsen et al., 1996a); the Army Corps of Engineers (ACE) cores were recovered as part of the currently-dormant Passaic River Diversionary Tunnel Project (Fedosh and Smoot, 1988; Olsen et al., 1996b). About 6.7 km of continuous core of mostly Triassic age, at a total of seven coring sites, was recovered by the NBCP, and over 10 km of mostly Jurassic core from dozens of coring sites is represented by the ACE cores. These cores have allowed the entire stratigraphy of all but the very oldest and very youngest parts of the Newark basin sequence to be recovered (Figure 4).

Based on these cores as well as outcrop studies, one of most dramatic features of the Newark basin sedimentary record is the pervasive cyclicity obvious in most of the sequence (Figure 5). This cyclicity was first described in detail, and ascribed to astronomical control of climate, by Van Houten (1962, 1964, 1969, 1980). All subsequent studies have confirmed and elaborated on these seminal works; the fundamental sedimentary cycle seen in these sequences, caused by the ~20 ky cycles of climate precession, has consequently been named the Van Houten cycle (Olsen, 1986).

The thickness of Van Houten cycles varies from about a meter to over 25 meters, depending on both the geographic and stratigraphic position in the basin, although within single formations in specific areas of the basin, the thickness tends to varies only about 25%. This cycle consists of three lithologically distinct divisions that are defined by the relative development, in comparison to surrounding units of sedimentary features and the presence of fossils indicative of submergence or exposure. These three divisions are termed 1, 2 and 3, and represent lacustrine transgressive, high stand, and regressive deposits, respectively (Figure 5). At one end of the range of expression of Van Houten cycles as seen in the Newark basin, they consist of very obvious asymmetrical sequences, that we interpret as produced by relatively wet conditions: 1, a relatively thin gray division 1, which has mud cracks or roots traces and often tetrapod footprints at the base, passing upward into oscillatory-rippled or laminated mudstone with no mudcracks, roots, or tracks; this division represents the transition from an exposed mud flat or vegetated plain to a perennial lake; 2, a moderately thick division 2, the lower part consisting of a black, microlaminated mudstone or limestone containing complete articulated fish and reptiles, produced by deposition in a deep (>80m) chemically-stratified lake; passing upward into less well laminated black or gray mudstones deposited in a perennial lake with an at least seasonally oxygenated bottom; 3, a thick division 3, marked by the presence of abundant mudcracks, and other signs of emergence, often with abundant tetrapod footprints, marking a the transition to temporally persistent playas and mudflats.

At the other end of the spectrum, even within the same more-inclusive stratigraphic sections, the Van Houten cycle can be dominated by red massive mudstone. We call this the "dry" type: 1, a red, nearly-imperceptible and abbreviated division 1, with barely-discernable mud cracks and/or roots, produced by a decrease in emergence of

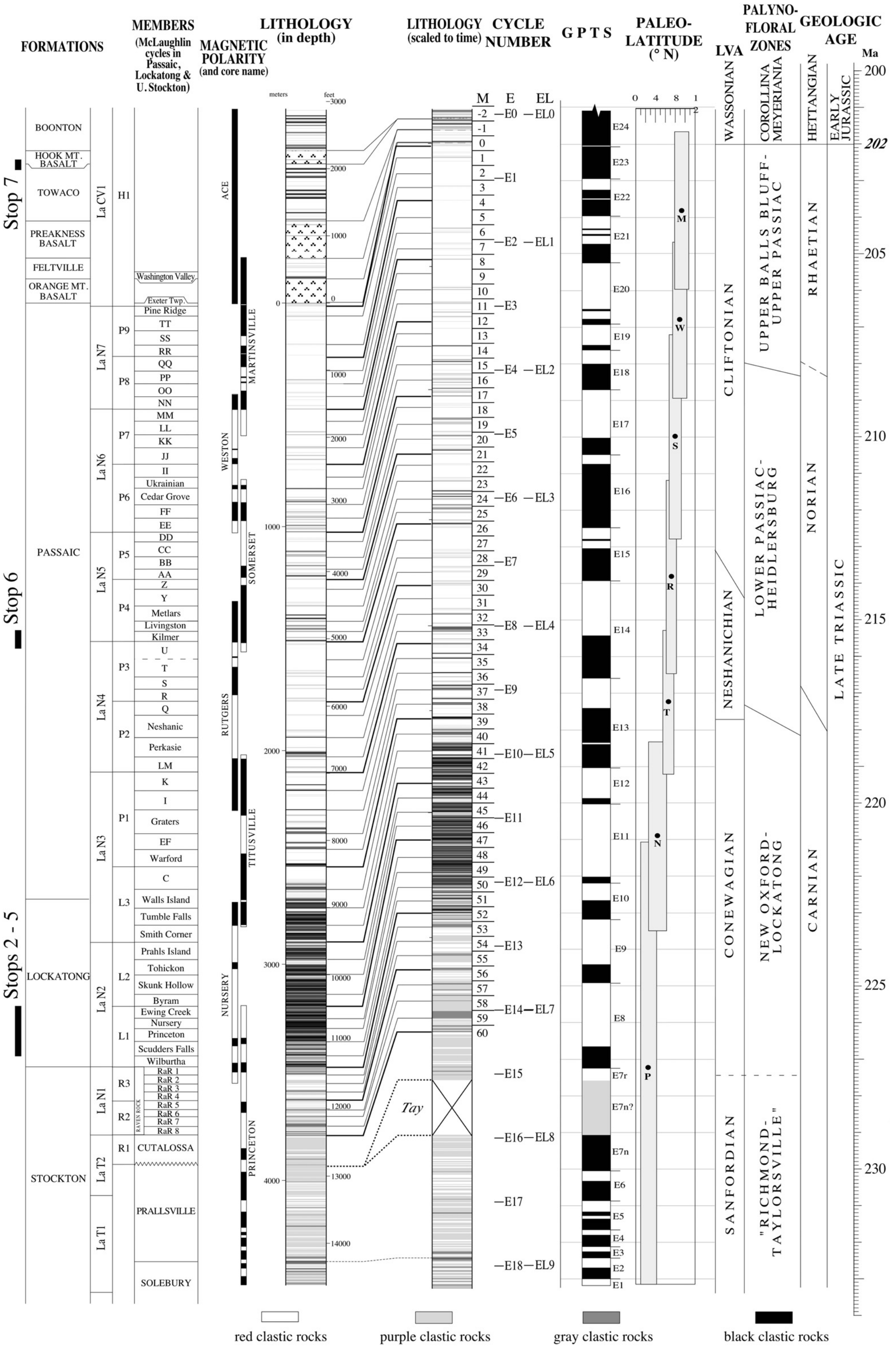

Figure 4. Newark basin section and time scale showing distribution of field stops (adapted from Olsen and Kent, 1999; Olsen et al., 2001a; Olsen et al., 2002b).

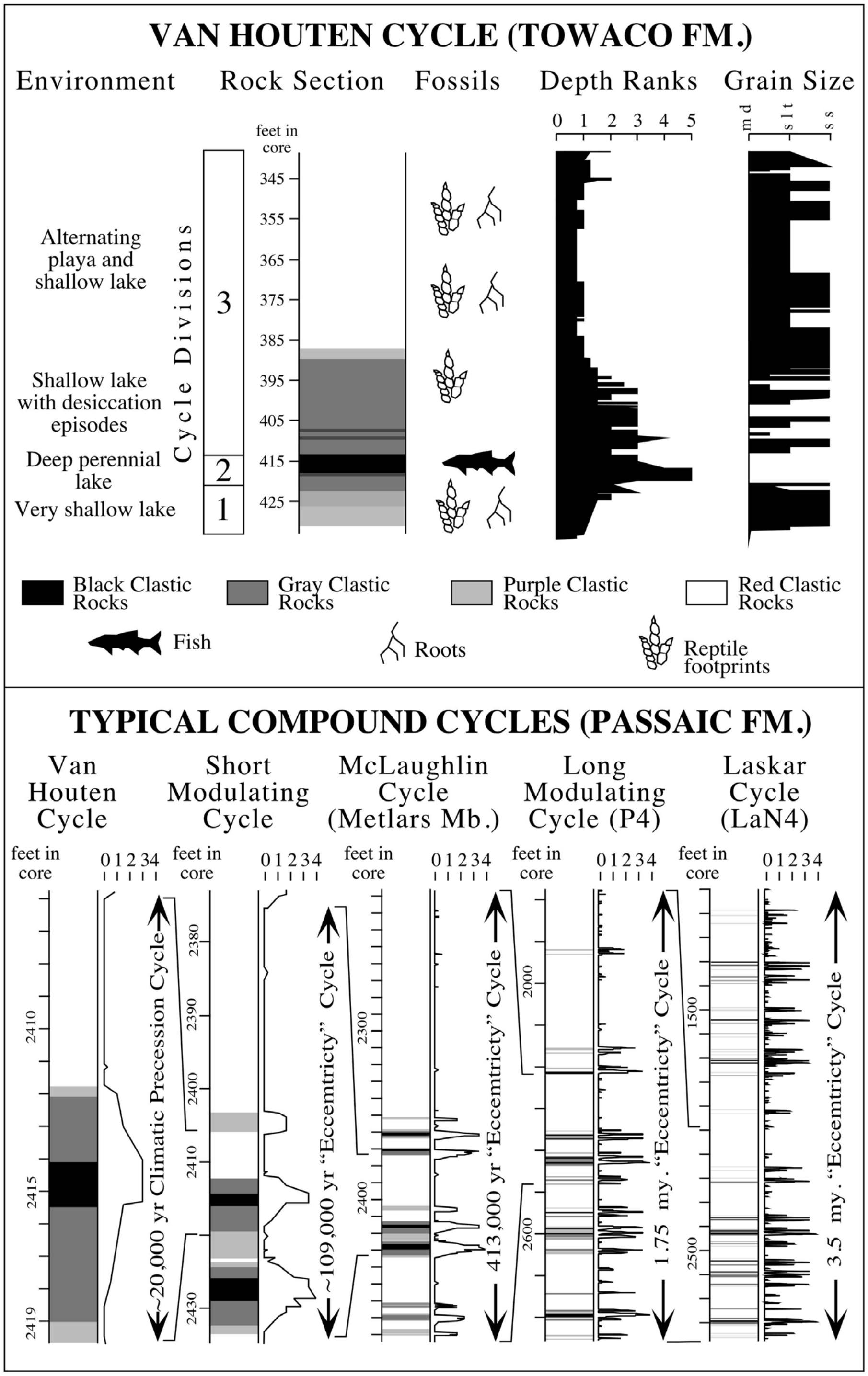

Figure 5. Van Houten and compound cycles (modified from Olsen and Kent, 1999).

the mud flat and an increase in sediment moisture; 2, a red division 2 with vague bedding and perhaps a trace of oscillatory ripples, deposited during sporadic episodes of standing water lasting years or decades; and 3, a division 3 consisting entirely of red massive mudstone, with virtually no visible structures except traces of permeating, superimposed mudcracks deposited during persistent playa conditions.

In vertical succession, the relatively wetness or dryness of Van Houten cycles is modulated by three orders of cycles, producing a characteristic and predictable pattern (Figure 5). The short modulating cycle consists of sequences of one to three relatively wet Van Houten cycles, followed by one to four relatively dry Van Houten cycles. The complete short modulating cycle usually has four to six Van Houten cycles; five cycles are less common. The short modulating cycle is the expression of the highest frequency of the so-called astronomical "eccentricity" cycles, which averages about 100 ky, although they are actually made up of two modes averaging 125 and 95 ky. Sequences of relatively "wet" short modulating cycles (i.e. dominated by wet types of Van Houten cycles) followed by relatively dry short modulating cycles make up the McLaughlin cycle (Olsen et al., 1996a), produced by the 404 ky cycle of eccentricity. This cycle is named for D.B. McLaughlin (1933, 1944, 1946), astronomer at the University of Michigan, who in his spare time mapped many of the 404 ky cycles over much of the Newark basin; ironically, there is no evidence that he ever ascribed the cyclicity to an astronomical cause. The long modulating cycle consists of four to five McLaughlin cycles, and following the pattern of the other modulating cycles, consists of one to three relatively wet McLaughlin cycles, followed by one to four relatively dry ones. This cycle was produced by a 1.75 my eccentricity cycle. Recent analysis reveals that alternations of relatively wet long modulating cycles with relatively dry ones marks out a 3.5 my modulating cycle (Olsen, 2001).

The two types of long modulating cycles (i.e. 1.75 and 3.5 my) find a counterpart in long time series of Neogene climatic precession where their values are 2.4 and 4.7 million years respectively. Laskar (1990, 1999) has shown that the former is caused by the interaction of the gravitational attraction of Mars and Earth, and that the value of the cycle is subject to considerable chaotic drift over time scales of hundreds of millions of years. Laskar (1990) has also shown the present 4.7 my cycle is a direct consequence of a resonance between the orbits of Earth and Mars, producing a cycle with a period twice that of the 2.4 my cycle. We ascribe the 1.75 and 3.5 million year Newark basin cycles to exactly the same mechanism, differing from the modern values because of planetary chaos, as predicted by Laskar (Laskar 1990; Olsen and Kent, 1999). We herein designate the 3.5 my long modulating cycle, as seen in the Newark lithostratigraphy, the Laskar cycle.

All of these astronomical cycles can be recognized by counting lithological cycles in the Newark basin record, either in outcrop or core (e.g. Van Houten, 1964). However, current quantitative determination of their periods in thickness relies on Fourier analysis carried out on numerically ranked sedimentary fabrics (depth ranks), color, or geophysical parameters (e.g. Olsen, 1986; Olsen and Kent, 1996, 1999; Reynolds, 1993). The periods in time are determined by calibration of the sedimentary record by assigning a 404 ky value to the McLaughlin cycle based on the total duration of the Newark basin Triassic section that is fully consistent with current paleontological correlations with existing radiometric time scales (Kent et al., 1995; Olsen and Kent, 1996). The 404 ky McLaughlin cycle in the Newark basin serves as a basis for an astronomically-calibrated geomagnetic polarity time scale for the Late Triassic (Olsen and Kent, 1996, 1999), which is pinned in absolute time by radiometric dates from CAMP igneous rocks (Figure

4). Use of the 404 ky cycle for time scale calibration for an interval hundreds of millions of years ago is justified because this eccentricity cycle is cause by the gravitational interaction of Jupiter and Venus, which should be stable on the scale of billions of years.

Stratigraphic Nomenclature

Traditionally, the Newark basin section has been divided into nine formal lithostratigraphic mappable formations (Figures 4) that generally do not correspond to the tectonostratigraphic divisions (Figures 3, 4) (Kümmel, 1897; Olsen, 1980a; Olsen et al., 1996a). These are, in ascending stratigraphic order: the Stockton Formation, consisting largely of fluvial tan and red sandstones and conglomerates and red mudstones, with less common gray sandstone and black and gray mudstone intervals (maximum thickness >2000 m); the Lockatong Formation, comprised of mostly cyclical gray and black mudstone, with less common red mudstones and sandstones of various colors (maximum thickness >1100 m); the Passaic Formation, made up of cyclical red, gray and black mudstones, sandstones and conglomerates, with red colors being dominant (maximum thickness >5000 m); the Orange Mountain Basalt, which consists of three major flows of high titanium quartz normative (HTQ) tholeiitic basalt (maximum thickness > +300 m) (Puffer and Lechler, 1980; Tollo and Gottfried, 1992); the Feltville Formation, a sequence with two black, gray, and red limestone cycles at its base, followed by vaguely-cyclical mostly-red mudstone, sandstone and minor conglomerate; the Preakness Basalt, made up of two major flows of high iron quartz normative (HFQ) basalt and one major flow of low titanium quartz (LTQ) normative basalt (maximum thickness > 300 m), with a minor red sedimentary interbed (Puffer and Student, 1992; Tollo and Gottfried, 1992); the Towaco Formation, comprised entirely of cyclical red, gray, and black mudstone, sandstone and conglomerate (maximum thickness >375 m); the Hook Mountain Basalt, made up of two major flows of high titanium, high iron, quartz normative (HFTQ) basalt (maximum thickness >150 m) (Puffer and Student, 1992; Tollo and Gottfried, 1992); and finally the Boonton Formation, which is closely comparable to the Towaco Formation (maximum thickness >500 m), except that there are more frequent thin gray beds, but less frequent microlaminated black mudstones.

The members of the Stockton Formation, as defined by McLaughlin, are based on grain size and very general lithologic character, while those of the Lockatong and Passaic Formation are comprised of individual McLaughlin cycles (e.g. McLaughlin, 1944; Olsen et al., 1996a) (Figure 4). The post-Passaic formations of the Newark basin have not been broken into members, with the exception of the limestone-bearing cycles of the lower Feltville Formation which are termed the Washington Valley Member (Olsen, 1980a).

In facies of the Lockatong and Passaic formations in which individual members cannot be traced with certainty, it is often possible to identify either the specific long modulating or Laskar cycles. Therefore, these have been given informal letter and number designations (Figure 4).

Definitions of the Stockton, Lockatong, and Passaic formations are based on gross lithologic features: the Stockton is characterized by the presence of abundant tan sandstones, coupled with infrequent gray and black mudstones; the transition from the Lockatong to the Passaic is based on the decrease in the frequency of gray and black mudstones in the latter. The boundaries between these formations are strongly time-transgressive along the axis of the basin, as illustrated by the fact that McLaughlin cycles of the Lockatong and Passaic Formation - which are defined as members, and which represent the 400 ky cycle - pass laterally between formations.

In the Newark basin, a high frequency of conglomerates correlates to the presence of abundant red beds. Thus the Lockatong Formation practically lacks conglomerates, while the Passaic Formation has abundant conglomerates at its northeastern and southwestern ends, including conglomerates that are laterally equivalent to the upper Lockatong Formation. In addition, parts of the lower Lockatong pass laterally into time-equivalent Stockton Formation at the northeastern and southwestern ends of the basin, especially along the Hudson River (see below), where this lithostratigraphic distinction becomes quite important when discussing the comparatively rich faunas from that area.

In contrast, the Jurassic age formations of the Newark basin are defined on the basis of separation by formations of very different lithology and origin; specifically, the alternation of basalt flow formations of distinct chemistry with intervening and overlying sedimentary formations of distinct character (Figure 4). The boundaries between these formations tend to be approximately isochronous, although there is probably some sedimentary onlap in the up-dip direction on top of each lava flow formation, as illustrated by the Feltville Formation (e.g. Olsen et al., 1996). Each of the Jurassic sedimentary formations includes some conglomerate near the border fault system and along the northeastern basin margin.

SUMMARY OF BASIN 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 the type “Atlantic passive margin” (e.g. Malinconico, 2002; Olsen, 1997; Schlische, 2002; Wintsch, 1997; Withjack et al., 1995, 1998). It has long been realized that regional extension relatively quickly followed the late Paleozoic compressive and oblique assembly of Pangea. However, the discovery of median Permian post-orogenic strata (TS I) requires the initiation of deposition, probably in extensional basins, perhaps due to orogenic collapse, very soon after the Late Carboniferous-Early Permian docking of Africa with North America. A depositional hiatus of perhaps 15 million years between TS I and II suggests a temporary cessation of plate divergence. Extension began in earnest in the Middle Triassic, marked by the formation of many relatively small basins that filled with TS II strata. At about 228 Ma, a larger pulse of extension, marked by the TS II – III unconformity, coalesced and enlarged many of these smaller basins, resulting in deposition of TS III in much larger basins. This was followed by the last known major pulse of extension at about ~201 Ma, which resulted in the emplacement of the intrusives and extrusives of the CAMP, and the deposition of the sediments of TS IV. All of these NW-SE-directed extensional pulses repeatedly reactivated appropriately-oriented Paleozoic compressional faults along which the rift basins formed, following the pattern demonstrated by Ratcliffe (1971) and Ratcliffe et al. (1986).

It appears that after more than 32 million years of extension in response to divergent plate motion, compression set in coaxial with the original extension direction.

In the Newark basin, the evidence is as follows: 1, dramatically higher thermal maturities (Malinconico, 2001) and reset zircon fission-track ages (Hoek et al., 1998; Steckler et al., 1993) along the eastern margin of the presently-delineated Newark basin, suggesting significant post-rift uplift and much more erosion of the eastern relative to western basin margin; 2, much if not most of the westward tilt of the Newark basin strata occurred post-depositionally, based on a pervasive mid-Jurassic paleomagnetic overprint, which itself also suggests a major mid-Jurassic fluid-flow event (Kent et al., 1995; Witte and Kent, 1991); 3, pervasive small-scale bedding-plane faults that show consistent reverse (in present coordinate space) motion based on offset of bedding-normal joints, small scale folds and thrust faults, and slickenline orientations that appear, on the basis of our casual observations, to be coaxial with the inferred older extension direction, thus requiring post-depositional NW tilting and NW-SE shortening in an approximately horizontal plane. These observations and interpretations are consistent with the basin inversion geometry described by Withjack et al. (1998). This geometry is based on physical models that produce a major up-arching of the basin during compression, but with little reverse motion on the boundary faults and only subtle compressional deformation of the basin fill. Erosion of several km of basin section and surrounding basement rocks took place during this late Early to Middle Jurassic tectonic inversion event. This was the second of similar events through the Mesozoic and Cenozoic which progressed from south to north all along the mid- to North Atlantic margin along crustal segments defined, on the east, by major strike-slip plate boundaries inherited from the Paleozoic assembly of Pangea. The segment containing the Newark, Hartford, Fundy and most of the Moroccan rift basins is bound by the Minas Fault – Gibraltar Fault zone on the north and the Long Island Platform boundary – South Atlas fault zone on the south (Figure 2).

By the Early Cretaceous the present erosional level had been reached in the Newark basin, and marine and marginal-marine Cretaceous and Cenozoic coastal plain deposits onlapped the rift deposits. Northwest-southeast compression slowed sometime in the Cenozoic switched to the NE-SW horizontal compression that persists to the present day (Goldberg et al., 2002; Zoback, 1992; Zoback and Zoback, 1989).

TECTONOSTRATIGRAPHIC SEQUENCES OF THE NEWARK BASIN AND THEIR DEPOSITIONAL ENVIRONMENTS AND PALEONTOLOGY

Tectonostratigraphic Sequence I

There is no compelling evidence for TS I in the Newark basin, although there are hints on the NB-1 seismic line that a pre-TS II package may be present adjacent to the border fault system (Schlische, 2002).

Tectonostratigraphic Sequence II

All of the Stockton Formation below the Cutaloosa Member appears to belong in TS II (Figures 4). This is based on magnetostratigraphic and lithological correlation between the upper Stockton Formation and the Newfound Formation (Taylorsville basin) that appears to reveal a small hiatus at the base of the Cutaloosa member (LeTourneau, 1999, 2002) that we consider to be the TS II – TS III unconformity. Lithostratigraphically, TS II consists of the Prallsville Member, made up of mostly tan and pink arkosic sandstone with minor conglomerate and red bioturbated red mudstone, and the underlying Solebury Member, comprised of tan and gray sandstone with proportionally more conglomerate and gray, black, and red mudstones. These members appear, at least in outcrop and existing core, to be mostly of fluvial origin, although the thin gray and black mudstones of the Solebury Member hint at lacustrine or paludal intervals. Analysis of the NB-1 seismic line suggests that the fluvial TS II sequences at the present-day surface might pass into lacustrine sequences at depth (Reynolds, 1993).

Paleontologically, TS II is virtually unprospected. The total assemblage known so far includes root traces, some cycadeoid compressions and silicified conifer wood (McLaughlin, 1959), the extraordinarily abundant arthropod burrow *Scoyenia*, and, most tantalizingly, from the base of the Solebury Member, a fragmentary mold of a jaw of *Calamops paludosus (Sinclair, 1917),* a very large, probably cyclotosaurian, amphibian (Figure 6). Cyclotosaurian amphibians are virtually absent from the rest of tropical Pangea, except the Middle Triassic (Anisian) age Moenkopi Formation of the western US, the Economy beds of the Fundy basin, assigned a Anisian age (Baird, 1986a; Olsen et al., 1989), and the upper part of unit T4 of the Timesgadouine Formation of the Argana Basin of Morocco (Dutuit, 1976; Jalil, 1996). This suggests that the basal Solebury Member could be part of the Economian faunachron of Lucas and Huber and Lucas (1993) and thus Middle Triassic in age. The Prallsville Member of the Stockton Formation is, thus far, devoid of fossils except *Scoyenia* and roots, but it probably is of early Late Triassic age, as is the upper part of TS II in other central Pangean rifts (Olsen, 1997). Additional prospecting in the Solebury and Prallsville members could be very rewarding, as TS II formations are by far the most fossiliferous portions of the stratigraphic sections in most of the rest of the eastern North American and Moroccan basins.

There is no evidence of TS II in the northeastern part of the Newark basin, near the Hudson River. The rapid decrease in outcrop width of the Stockton from Princeton towards the Hudson is probably due to a combination of progressive onlap of younger TS II onto basement, and truncation of younger beds of TS II by the TS II – TS III unconformity (Figures 3, 7).

Tectonostratigraphic Sequence III

In the Newark basin, TS III is by far the most widespread and, at least in outcrop, the most heterogeneous portion of the basin fill, consisting of the Cutaloosa and Raven Rock members of the Stockton Formation, the entire Lockatong Formation, and nearly all of the Passaic Formation. This sequence is characterized by the dominance of cyclical lacustrine and laterally-equivalent marginal lacustrine and fluvial strata. It is richly fossiliferous, especially in the northeastern part of the basin.

The Cutaloosa and Raven Rock members are poorly known. The former appears to be the basal coarse-grained sequence of TS III. The latter consists of thick cycles of gray and tan sandstone with subordinate black and gray mudstones, overlain principally by red mudstones and tan sandstones. Relatively large-scale sets of tilted surfaces are abundant in the outcropping Raven Rock Member in the central Newark basins, and

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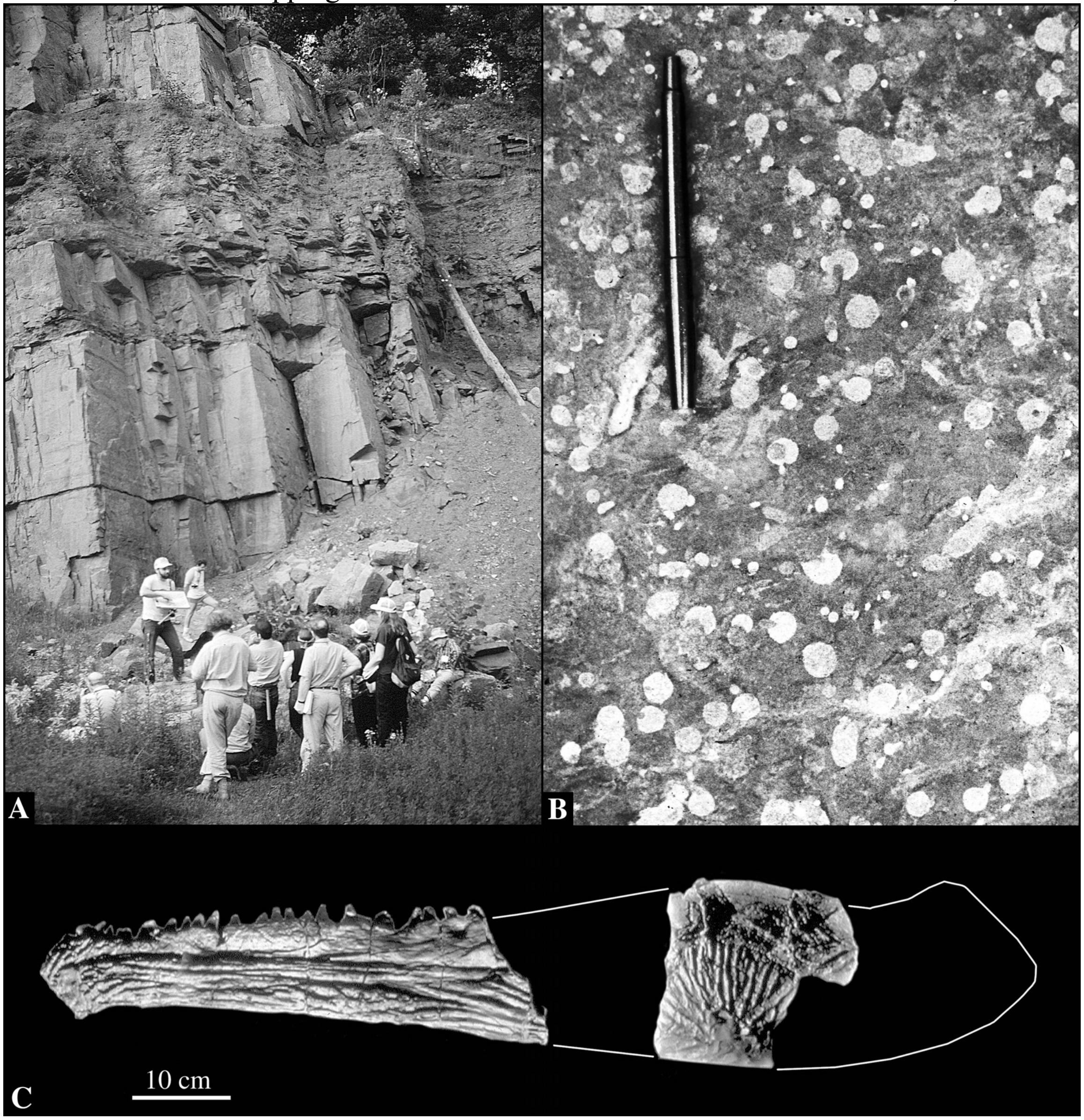

Figure 6. Facies and fossils from Tectonostratigraphic sequence II. **A**, quarry in Prallsville Member of the Stockton Formation, Prallsville, New Jersey. **B**, *Scoyenia* burrows in red-purple siltstone from same quarry as in A; **C**, rubber cast of natural mould comprising type and only specimen of the giant ?Capitosaurid amphibian *Calamops paludosis* near the base of the Solebury Member of the Stockton Formation (photo courtesy of W. Seldon and D. Baird).

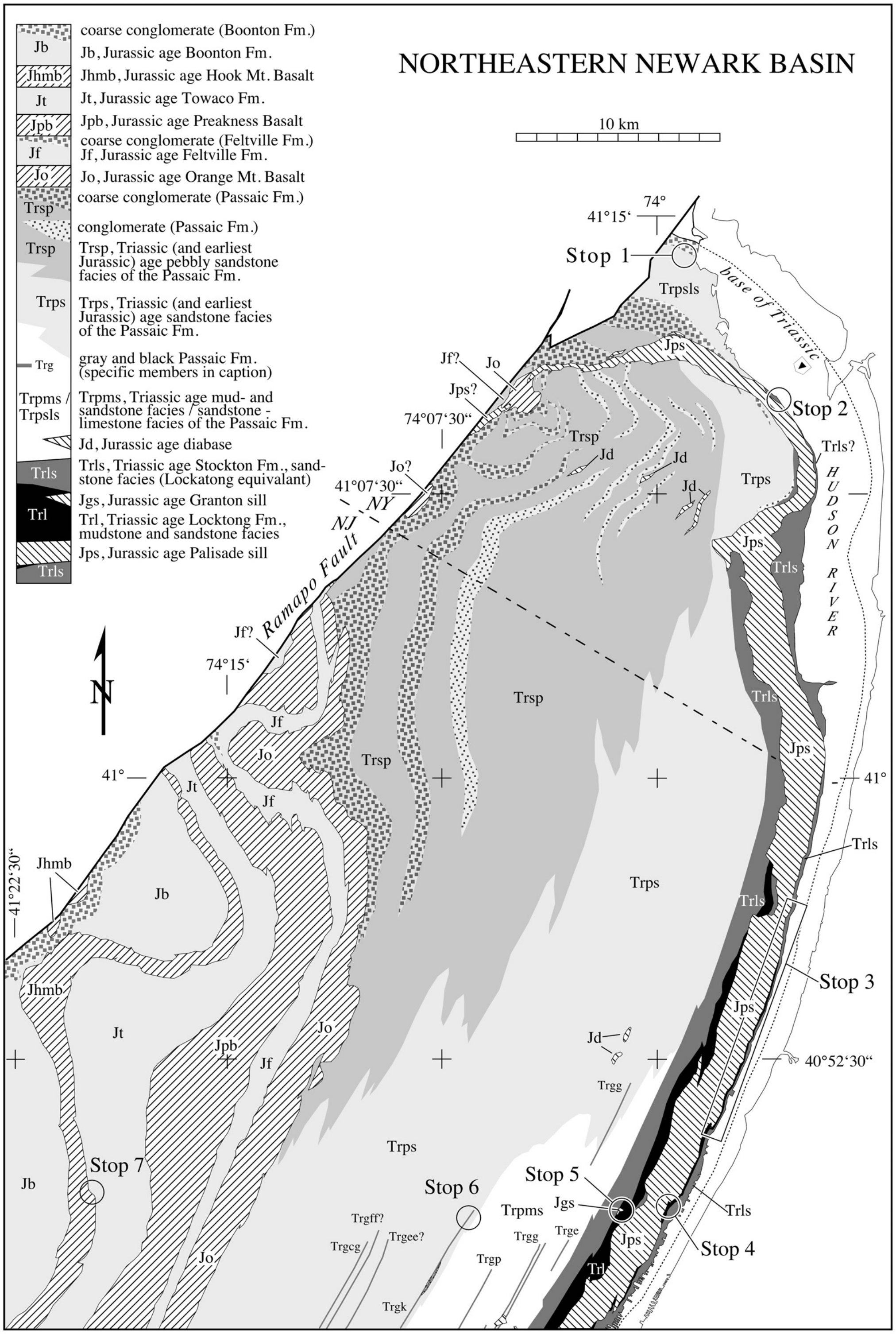

Figure 7. Bedrock geological map of the northern Newark basin showing the field stops (Based on Ratcliffe, 1999; Parker, 1993; Parker et al., 1988; and Olsen et al., 1996a).

many convincingly appear to be lacustrine deltaic sequences (Smoot, 1991; Turner-Peterson and Smoot, 1985). The large-scale cycles, tens of meters thick, appear to be a coarser, more proximal expression of McLaughlin cycles (Olsen and Kent, 1999), in which the small-scale cycles are masked by both the large size of the sedimentation units and depositional surface relief. Reynolds (1993) has shown that the Raven Rock Member passes down-dip into a seismic facies indistinguishable from the Lockatong Formation, suggesting the subsurface presence of a time-equivalent of the Raven Rock Member that is more like the Lockatong in cyclical style and sedimentary facies. This is consistent with magnetostratigraphic correlation to the more southern Newark Supergroup basins, that indicates the well-developed cyclical lacustrine strata of the lower member of the Cow Branch Formation, lower Port Royal Formation, and Cumnock Formation, are time equivalents of the lower Raven Rock Member.

Strata of the Raven Rock Member are paleontologically poorly prospected. The known assemblages consist of a single palynoflora (Cornet, in Olsen and Flynn, 1989), a relatively rich compression plant assemblages (Ash, 1986; Axsmith and Kroehler, 1989; Bock, 1952; McLaughlin, 1959), clams from several localities (Axsmith and Kroehler, 1989; Olsen and Flynn, 1989) *Scoyenia*-type burrows, conchostracans, and beetle elytra (Axsmith and Kroehler, 1989; Olsen and Flynn, 1989) (Figure 8). These assemblages are consistent with an early Late Triassic (Late Carnian) age. Again, the fossil record of age-equivalent strata in the more southern basins suggests that careful prospecting will be well rewarded.

The overlying Lockatong Formation consists almost entirely of dramatically cyclical mudstone; these cycles are the most fossiliferous in the Newark basin section (Figure 8). The full suite of lithological cycles attributed to astronomical forcing is present. In general, the most fossiliferous Van Houten cycles tend to be those in the wettest phases of the 3.5 my Laskar cycle, 1.75 my long modulating cycles, 404 ky McLaughlin cycle, and 100 ky short modulating cycles . These include the Princeton, Nursery and Ewing Creek members of the lower Lockatong, the Skunk Hollow and Tohickon members of the middle Lockatong, and the Smith Corner and Walls Island members of the upper Lockatong, although the latter have hardly been prospected.

In the central part of the Newark basin along the Delaware River, Van Houten cycles average about 5.5 m thick, short modulating cycles average about 25 m thick, McLaughlin cycles average 100 m thick, the long modulating cycles average 440 m thick, and the Laskar cycles, 880 m. In both outcrop and available core, the cycles thin away from this area, but in the subsurface to the west, they probably thicken.

Plant assemblages are surprising rare in the Lockatong; described assemblages consist of a single palynoflorule (Cornet, in Olsen and Flynn, 1989) and a few cycadeoid, conifer and equisetalian compression fossils and molds (McLaughlin, 1959; Olsen and Flynn, 1989) in gray and purple mudstones and fine sandstones. However, animal remains can be exceedingly common. Invertebrates found so far include: several types of clams (Heath and Good, 1996; McLaughlin, 1959; Olsen and Flynn, 1989) from gray platy mudstones and ripple cross-laminated fine-grained sandstones; *Scoyenia* and various other trace fossils (Metz, 1995b); burrows in red, gray and purple mudstones and sandstones; spectacularly abundant conchostracans, darwinulid ostracodes; and a single undescribed large crustacean in black to gray laminated to microlaminated mudstones. Vertebrate body fossils are very strongly dominated by a stereotyped assemblage of

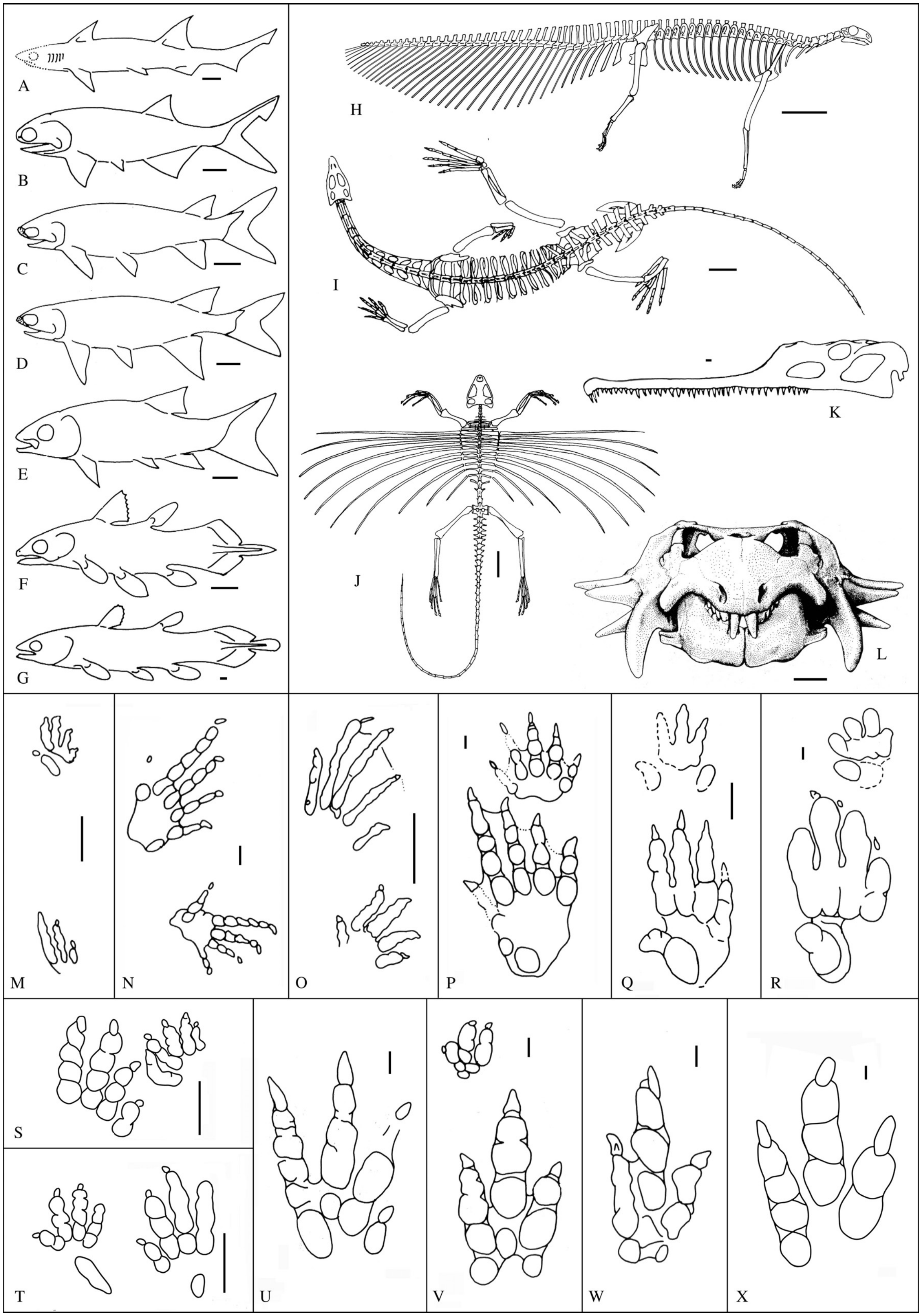
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Figure 8. Representative vertebrates from Tectonostratigraphic Sequence III of the Newark basin (modified from Olsen, 1988; Olsen and Flynn, 1989): **A**, the freshwater shark *Carinacanthus jepsoni* (Lockatong Fm.); **B**, the palaeoniscoid *Turseodus* (Lockatong Fm.); **C**, the palaeonisciform *Synorichthyes* (Lockatong and Passaic fms.), **D**, the palaeonisciform *Cionichthyes* (Lockatong and Passaic fms.); **E**, the holostean *Semionotus* (Lockatong and Passaic fms.); **F**, the small coelacanth *Osteoplurus newarki* (Lockatong Fm.); **G**, the large coelacanth cf. *Pariostegeus* (Lockatong Fm.); **H**, the drepanosaurid diapsid *Hypuronector limnaois*; (Lockatong Fm.); **I**, the tanystropheid diapsid *Tanytrachelos ahynis* (Lockatong Fm.); **J**, the lepidosaur *Icarosaurus seifkeri* (Lockatong Fm.); **K**, rutiodontid phytosaur *Rutiodon* (Lockatong and Stockton fms.); **L**, the parareptile *Hypsognathus fenneri* (Passaic Fm.); **M**, the probable lepidosauromorph track *Rhynchosauroides brunswickii* (Lockatong and Passaic fms.); **N**, the probable diapsid reptile track *Rhynchosauroides hyperbates* (Stockton, Lockatong, and Passaic fms.); **O**, the probable tanystropheid track *Gwynnedichnium* (Lockatong and Passaic fms.); **P**, the phytosaur track *Apatopus lineatus* (Stockton, Lockatong, and Passaic fms.); **Q**, the probable aetosaurid archosaur track *Chirotherium lulli* (Passaic Fm.); **R**, the probable rauisuchian archosaur *Brachychirotherium parvum* (Stockton, Lockatong and Passaic fms.); **S**, the ?sphenosuchian track "new taxon A" (Passaic Fm.); **T**, the probable crocodiliomorph track *Batrachopus bellus* (Passaic Fm.); **U**, the dinosaurian track "new genus 1" (Passaic Fm.); **V**, the ornithischian dinosaur track *Atreipus milfordensis* (Stockton, Lockatong, and Passaic fms.); **W**, the theropod dinosaur track *Grallator* (Stockton, Lockatong, and Passaic fms.); **X**, the theropod dinosaur track *Anchisauripus* (Passaic Fm.). Scale is 1 cm.

aquatic and lake margin forms, including, from microlaminated mudstones, abundant and fairly diverse articulated fish and small diapsid reptiles, and phytosaur teeth (Figure 8). Less well-laminated mudstones sometimes have disarticulated remains of the same kinds of vertebrates; occasional pockets of small tetrapod bones occur in more massive gray and red mudstones. Tetrapod footprints can be very abundant in divisions 1 and 3 of Van Houten cycles, and include one spectacularly well-preserved assemblage (Figure 8). Vertebrate coprolites are common in many facies. As a rule, vertebrate fossils are much more common outside of the microlaminated units in marginal facies of the Lockatong, especially where well-developed deltaic deposits are present in division 3 of the Van Houten cycles. The one facies of the Lockatong in which fossils of all kinds are very rare is the gray and red mudcracked massive mudstone characteristic of division 3 of the Van Houten cycles, especially in the dryer phases of the McLaughlin, long modulating, and Laskar cycles.

In the northeastern Newark basin (Figure 9), the outcrop belt of the Lockatong on both sides of the Palisade sill along the Hudson River is remarkably rich in vertebrate fossils, despite varying degrees of contact metamorphism. In this region, virtually all fine-grained facies and all cycles have some vertebrate body fossils. Here, only the Princeton, Nursery, and Ewing Creek members of the Lockatong Formation have been positively identified (see Stops 4-6). Van Houten cycles thin to an average of about 1.5 m in this region, and at least some cycles from the drier phases of the 404 ky McLaughlin cycles appear to be entirely missing or replaced by tan arkose. The couplets (i.e. varves) of microlaminated mudstones are thinner than their counterparts towards the center of the basin, but not in proportion to the thickness of the cycles, again suggesting a preferential omission of drier facies in each cycle.

A notable feature of the microlaminated portions of division 2 of the Van Houten cycles near the Hudson River is the truly remarkable abundance of fish, especially the coelacanth *Osteopleurus newarkii*, the palaeoniscoid *Turseodus* spp. and the holostean *Semionotus braunii*, as well as two genera of small tetrapods, the tanystropheiid prolacertian archosauromorph diapsid *Tanytrachelos ahynis*, and the bizarre drepanosaurid diapsid *Hypuronector limnaios*, (Colbert and Olsen, 2001; the "deep tailed swimmer" of Olsen, 1980a) (Figure 8). Less common in the same units is a large coelacanth, probably *Pariostegeus* sp., the redfieldiid palaeonisciform fish *Synorichthyes* and *Cionichthyes*, the gliding lizard-like lepidosauromorph diapsid *Icarosaurus seifkeri*, and phytosaur teeth. More massive mudstones of division 3 of the Van Houten cycles usually have scraps and sometimes more complete remains, including a skull (Colbert, 1965), of phytosaurs; metoposaur amphibian fragments (e.g. AMNH 23579); and locally-common fish fragments and coprolites, even in mudcracked beds. Only a few poorly preserved reptile tracks, all small probable-dinosaurian forms, have been found (e.g. Gratacap, 1886).

Strata mapped as Stockton Formation along the Hudson River are almost certainly time-equivalents of the lower Lockatong Formation, and the transition from typical Lockatong (i.e. lacustrine) facies to Stockton (i.e. fluvial) facies in the Princeton and Nursery Members can be observed along the river, going north from Hudson and Bergen counties (New Jersey) into Rockland County (New York) (Figure 7). A particularly distinctive facies of the Stockton, probably the lateral equivalent of the Scudder Falls and Wilbertha members of the basal Lockatong, occurs below the Princeton Member along the Hudson River from at least Hoboken to Alpine (New Jersey), with similar facies occurring sporadically at least to Snedens Landing (New York). This facies consists of meter-scale cycles of tan cross-bedded coarse-grained or pebbly arkose passing upward into mottled or streaked purple, red and tan arkosic sandstone, and then upward into bright purplish-red massive mudstones, that often have large, widely spaced ?shrinkage cracks filled with arkose from the overlying cycle. This facies has produced one notable fossil, a partial post-cranial skeleton of a large phytosaur named *Rutiodon manhattanensis* (von Huene, 1913), found near the west abutment of the George Washington Bridge (see Stop 3g).

Passing further to the north along the Hudson into Rockland County, the Lockatong Formation disappears, having passed laterally into the Stockton Formation. From Piermont northward to Haverstraw, the Stockton consists of alternations of decameter-scale 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 McLaughlin cycles, but cannot demonstrate this. Both types of sequences contain abundant fossils, including bones (see Stops 2 and 3).

Reptile tracks, *Scoyenia*, and root traces are common in the mostly-red facies, while the drab facies contains bones, tracks and root traces. So far, the osteological remains include phytosaur teeth and bone scraps, a small amphibian dermal bone, unprepared portion of a tetrapod skull or vertebra, and numerous indeterminate bone fragments. This material, while scrappy, is very important because it represents more terrestrial communities than the temporally equivalent assemblages in the Lockatong . Reptile tracks include poorly preserved trackways from Blauvelt (NY), which have been widely assigned to grallatorid ichnotaxa, and even attributed to the ceratosaurian theropod dinosaur *Coelophysis* (Fisher, 1981). However this designation is probably incorrect, and in fact the tracks more likely belong to *Atreipus* isp., which was most likely made by an ornithischian dinosaur (Olsen and Baird, 1986). Other tracks are much better preserved and include a true small grallatorid, unquestionable *Atreipus*, the (?)phytosaurian track *Apatopus*, the probable-rauisuchian archosaur track *Brachychirotherium* sp., and the lepidosaurian track *Rhynchosauroides* cf. *R. hyperbates* and related traces (Figure 8). According to Huber and Lucas (1993) and Lucas and Huber (2002), the tetrapods of the Lockatong and equivalent-age strata indicate inclusion in the Conewagian faunachron of Late Carnian age.

The Passaic Formation conformably overlies the Lockatong Formation in most of the Newark basin, and for the most part continues the cyclical pattern seen in the latter (Figures 4, 5). In the two central basin fault blocks near the Delaware River, the transition from Lockatong to Passaic occurs in precisely the same cycles (Olsen et al., 1996a). The lowermost Passaic is marked by an abrupt switch to much more abundant red massive mudstone in the upper half of the Walls Island Member, as well as an increase in Van Houten cycle thickness of about 33%, seen in both outcrop and core. As is the case of the underlying Lockatong, cycle thickness in the Passaic Formation decreases west, east, and northeast of this central area. Cycle thickness increases in outcrop and presumably in the subsurface to the west towards the border fault. However, away from the center of the basin, the transition occurs at lower stratigraphic levels, but most of the individual members are still identifiable.

Overall, the apparent wetness of the Lockatong and Passaic formations decreases cyclically upward. 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 and massive vesicular fabric in division 3 of the Van Houten cycles (Smoot, 1991). 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 TS III (c.f. Schlische and Olsen, 1990).

It is only recently that the paleontological richness of the Passaic Formation has become appreciated. Far from being a "monotonous sequence of red beds" devoid of fossils, the Passaic Formation is in fact very fossiliferous in the basin margin facies (Figure 8). There are many palynoflorules recovered from the TS III portion of the Passaic formation (Cornet, 1977; Cornet and Olsen, 1985; Fowell, 1993; Fowell and Olsen, 1993), several significant macrofossil assemblages (Cornet, 1977; McLaughlin, 1959), and root traces are very common in many areas and facies. Invertebrates include abundant *Scoyenia* as well as other trace fossils (Metz, 1993, 1995a, 1998), conchostracans and ostracodes in gray to black portions of division 2 of the Van Houten cycles, and from one locality, insects, apparently dipteran (fly) larvaeFish are much more rare in the Passaic than in the Lockatong; this correlates with both the much lower frequency of microlaminated strata as well as a lack of prospecting. The only articulated fish are *Semionotus*, from several localities in the black shale of division 2 of one Van Houten cycle near the base of the Warford Member (Late Carnian), the same basic facies in the Ukrainian Member (Rhaetian), and a gray laminated siltstone in Member L-M (early Norian or latest Carnian). Disarticulated fish occur at a number of localities, and include fragments of small coelacanths and redfieldiids (member I, Late Carnian or Norian age; Olsen et al., 1982) and complete *Semionotus* (Warford Member, Late Carnian age; member OO, middle Rhaetian).

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, particularly the Jacksonwald syncline (Figure 8). Initially in the Passaic Formation(Carnian and early Norian), the ornithischian dinosaurian form *Atreipus* is very abundant, but its last known occurrence is in the Rhaetian (members II and JJ). The abundance and size of grallatorid theropod dinosaurian tracks, traditionally (e.g. Lull, 1953) placed in the ichnogenera *Grallator* and *Anchisauripus*, increase through the Passaic in TS II, and they are the only dinosaurian forms in Late Rhaetian aged strata. There are, however, diverse other ichnogenera in the Passaic, representing procolophonids, tanystropheids, lepidosauromorphs, and various (phytosaurian, aetosaurian and rauisuchian) archosaurs (Figures 8, 10).

Discoveries of osteological tetrapod remains are becoming increasingly common. In particular, red and gray massive root-bearing sandstones and siltstones have abundant remains locally. Thus far, skeletal material includes fragments to articulated partial skeletons of metoposaurid amphibians, the procolophonid *Hypsognathus fenneri*, phytosaurs, the aetosaur *Aetosaurus (Stegomus) arcuatus*, and the crocodylomorph *Protosuchus*, as well as unidentified forms. As an example of how rich the Passaic can be, one locality in the Jacksonwald syncline (member TT), has produced several hundred specimens of *Hypsognathus*, including five skulls and three partial skeletons.

The Van Houten cycles so obvious in some parts of the basin gradually become less well-marked as we progress into the coarser facies of the Passaic Formation in the northeastern part of the basin; therefore some important fossil localities cannot be placed in a specific McLaughlin cycle. Nonetheless, the position within the long modulating and/or Laskar cycles can still be ascertained. In the northeastern Newark basin, the TS III portion of the Passaic has yielded two palynoflorules (in the Cedar Grove Member, and the upper part of long modulating cycle P4), one compression flora assemblage (from the latter palynofloral locality), one major footprint locality (lower part of long modulating cycle P4), a minor footprint locality that nonetheless has produced significant forms (lower Laskar cycle LaN7; Baird, 1986b); and surprisingly abundant remains of *Hypsognathus fenneri* from several localities (Laskar cycles LaN5, LaN6, and LaN7; Colbert, 1946; Gilmore, 1928; Sues et al., 2000), as well as tooth and bone fragments of indeterminate tetrapods from several localities. The relatively common *Hypsognathus* and indeterminate scraps indicate that every red sandstone outcrop or temporary exposure should be carefully examined.

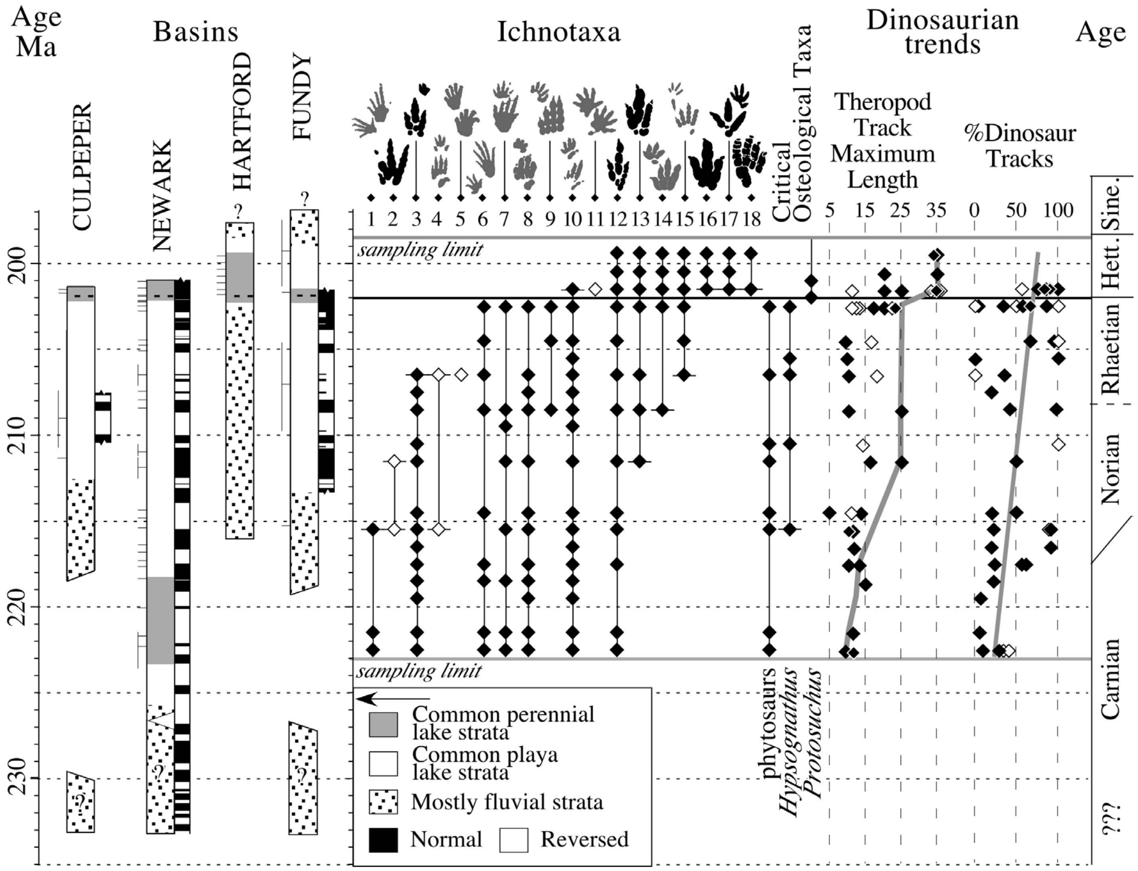

Figure 10. Correlation of four key basins of the Newark Supergroup showing the temporal ranges of footprint ichnogenera and key osteological taxa binned into 1 my intervals showing the change in maximum theropod dinosaur footprint length (line drawn through maximum) and percent of the assemblages that consist of dinosaur tracks (with linear regression line). Short, horizontal lines adjacent to stratigraphic sections show the position of assemblages and the attached vertical lines indicate the uncertainty in stratigraphic position. Ichnotaxa are: 1, *Rhynchosauroides hyperbates*; 2, new dinosaurian genus 1; 3, *Atreipus*; 4, *Chirotherium lulli*; 5, *Procolophonichnium*; 6, *Gwyneddichnium*; 7, *Apatopus*; 8, *Brachychirotherium parvum*; 9, new taxon B; 10, *Rhynchosauroides* spp.; 11, *Ameghinichnus*; 12, "*Grallator*"; 13, *Anchisauripus*; 14, *Batrachopus deweyii*; 15, "*Batrachopus*" *gracilis*; 16, *Eubrontes giganteus*; 17, *Anomoepus scambus*; 18, *Otozoum moodii*. Stratigraphic and magnetostratigraphic columns and correlations modified from (Olsen, 1997) (from Olsen et al., 2002b).

Tectonostratigraphic Sequence IV

Based on lithostratigraphic and magnetostratigraphic correlations laterally over distances greater than 100 km, the TS III – IV contact is a correlative conformity over much of the Newark basin with liittle evidence for a tectonostratigraphic sequence boundary, probably because of the very deep level of post-rift erosion. However, in the northeastern Newark basin, northeast of East Orange (NJ), there is an abrupt change in facies from coarse red sandstone, conglomerate, and massive mudstone below, to much better-bedded sandstones and mudstones above, characteristically with very abundant reptile footprints. This transition could represent the TS III - IV boundary. Further northeast near Ladentown (NY), the Passaic Formation thins dramatically below the Orange Mountain Basalt, coincident with an abrupt change in strike, which could be due to truncation by the TS III – IV unconformity (Figure 7). The evidence for a well-developed TS III – IV unconformity is, however, far from conclusive. It is very important to stress that the TS III – IV boundary and any associated unconformity occurs well below the palynologically-identified Triassic-Jurassic boundary. There is no evidence for - and much against - an unconformity or hiatus at the Triassic-Jurassic boundary in the Newark basin (Fowell and Olsen, 1993, 1995; van Veen, 1995).

TS IV sedimentary sequences show a development of persistent lacustrine conditions of a magnitude not seen since the Lockatong, some 16 million years earlier (Figure 4). This transition occurs at the base of the Pine Forge Member and continues in the strata between and above the extrusive basalt formations. As a consequence, sedimentary units of TS IV are very rich in floral remains, fish, and reptile footprints (Figure 9).

The floral assemblages of TS IV consist of stromatolites around trees from a single locality (middle Towaco Formation), common palynomorph assemblages from many gray units, several important compression fossil assemblages, and root traces (Figure 9). Most gray units produce palynomorph fall into two groups, that allow us to recognize the Triassic-Jurassic boundary. Palynomorph assemblages from the Pine Ridge and lower Exeter Township members are diverse and tend to have varying proportions of the Triassic taxon *Patinasporites densus*, along with other Triassic forms, and varying amounts of *Corollina* spp. (this genus never exceeding about 60% of the assemblage). Strata of the upper Exeter Township Member and the remainder of TS IV lack Triassic taxa and are overwhelmingly dominated by *Corollina* (Cornet, 1977; Fowell, 1993; Fowell and Olsen, 1993; Olsen et al., 1990), with only minor variations in the composition of palynomorph assemblages. The transition has been studied most intensively in the Jacksonwald syncline, where the two types of assemblages are separated by only 5 meters of strata (Figure 11). A thin (20-30 cm) interval, about 70 cm above the last Triassic palynoflorule, is dominated by fern spores. We regard the base of this “fern spike” unit as the Triassic-Jurassic boundary (Fowell et al., 1994; Olsen et al., 2002b,c).

Macrofloral compression assemblages occur in every formation in TS IV and tend to be in the same strata as the palynomorph assemblages. An important but structurally poorly-preserved assemblage occurs in the uppermost Passaic Formation near the Clifton-Paterson (NJ) town boundary. This assemblage is dominated by several forms of *Brachyphyllum*-type conifer shoots, conifer cone fragments, and leaf fragments of the fern *Clathropteris meniscoides*. A very poorly preserved palynoflorule from this assemblage contains only *Corollina*, suggesting a Jurassic age, probably (based on cycles) less than 10 ky younger than the Triassic-Jurassic boundary. Beautifully preserved compression assemblages in gray mudstones - particularly from several localities in the Oldwick Syncline in the Washington Valley Member - produce abundant

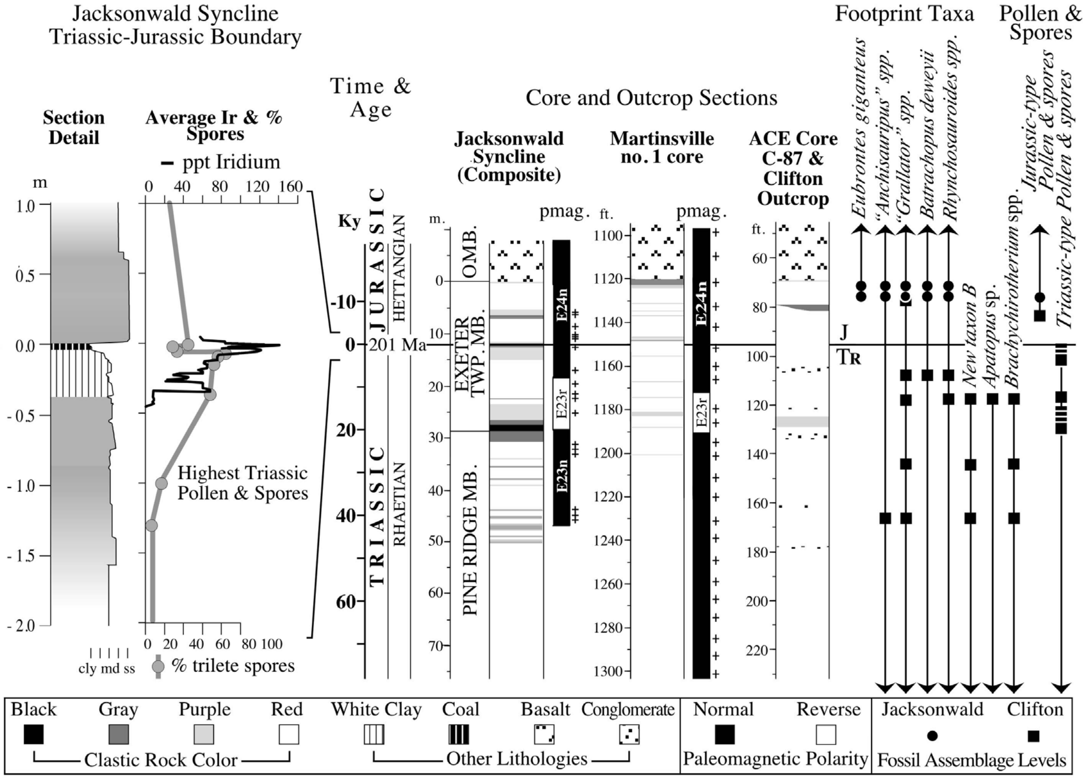

Figure 11. Fine-scale correlation between Ir anomaly, and fern spike, and footprint data from the Newark basin (from Olsen et al, 2002b). Average Ir anomaly is based on 4 localities along strike each of which have an Ir anomaly in virtually identical position (details of data and averaging in supplemental material).

Brachyphyllum shoots and associated reproductive structures . Large fronds of *Clathropteris meniscoides* in growth position have been found in gray ripple cross-laminated siltstone of this member. Conifer shoots and reproductive structures, stems of the horsetail rush *Equisetites*, and rare fragments of *Clathropteris* and the cycadeoid *Otozamites* occur in gray siltstones and claystones of the Towaco and Boonton formations (Cornet, 1977). The stereotyped nature of these assemblages stands in stark contrast to the typical Triassic assemblages from the rest of the Newark Supergroup.

Invertebrates from TS IV include various trace fossils (Metz, 1984, 1991, 1992; Boyer, 1979) with *Scoyenia* being notably rare or absent, darwinulid ostracodes and conchostracans (Pine Forge and Exeter Township members of the Passaic, and Washington Valley Member of the Feltville) (e.g. Nason, 1889; Olsen, 1980a), and an elytron of the beetle *Liasocupes* sp. (Huber et al., 2002). All of these occur in gray thin-bedded, although not microlaminated, silty claystones and limestones.

Articulated and often beautifully-preserved fish are abundant in microlaminated beds of division 2 of Van Houten cycles in the Feltville, Towaco, and Boonton Formations. These include the large coelacanth *Diplurus longicaudatus* (Boonton Formation), the palaeonisciforms *Ptycholepis marshi* (Feltville Formation) and *Ptycholepis* sp. (Boonton Formation), the redfieldiid palaeonisciform *Redfieldius* spp.

(Feltville and Boonton formations), and the holostean *Semionotus* spp. (all formations). In contrast to the Triassic examples, the *Semionotus* spp. comprise species flocks comparable to those seen in cichlid fishes in the Great Lakes of East Africa (McCune, 1987, 1996; McCune et al., 1984; Olsen, 1980a). Some of the fish from TS IV are among the best preserved early Mesozoic fish from anywhere (e.g. Olsen and McCune, 1991).

Tetrapod footprints are more common in TS IV sedimentary units than in any other part of the Newark basin section, with a few localities having produced perhaps tens of thousands of specimens. Three footprint assemblage types occur within TS IV. The oldest is restricted to TS IV strata below the palynologically-identified Triassic-Jurassic boundary (Pine Ridge and lower Exeter Township members of the Passaic Formation), 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 a form of probable crocodylomorph affinities referred to as New Taxon B (Silvestri and Szajna, 1993) and abundant specimens of the theropod dinosaurian forms *Grallator* spp. and *Anchisauripus* spp. (Figure 10, 11). The second type of assemblage occurs directly above the Triassic-Jurassic boundary (upper Exeter Township Member, Passaic Formation) 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 localities occur in strata directly beneath the Orange Mountain Basalt, at several former and presently active quarries in the northeastern part of the 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 (upper Towaco Formation – see Stop 7), and *Rhynchosauroides* sp. is restricted to a single specimen from the same approximate level as *Ameghinichnus* (Olsen, 1995). The tetrapod footprint assemblages thus follow the turnover pattern seen in the palynofloral assemblages.

In contrast to the exceedingly abundant and well-preserved tetrapod footprint assemblages, osteological remains from the Jurassic of the 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 (Olsen, 1995)!

TRIASSIC AND JURASSIC CONTINENTAL COMMUNITIES AND THE TRIASSIC-JURASSIC BOUNDARY

The superb time control and resolution provided by the astronomically-calibrated paleomagnetic polarity timescale makes the Newark Supergroup, particularly the Newark basin, one of the best venues for examining tropical continental floral and faunal change across the Triassic-Jurassic boundary (Kent and Olsen, 1999; Olsen and Kent, 1999). Its one deficit, as cited by Benton (1994), has been a lack of osteological remains of tetrapods, but this is rapidly being remedied (Carter et al., 2001; Olsen et al., 2000b, 2001b; Sues et al, 2000). Based on the Newark timescale and paleontological correlations with areas outside the central Pangean rift zone, a consistent picture emerges of the profound changes that occurred around the boundary, with some indications of what the causal mechanism for that change may have been.

During the Late Triassic, there were several floral provinces that closely paralleled the geographic distribution of the provinces present during the Permian, and apparently followed largely-zonal climate belts. There was a vast Gondwanan province in the Pangean southern hemisphere dominated by the pteridosperms *Dicroidium* and *Thinnfeldia* (Anderson and Anderson, 1970; Olsen and Galton, 1984), approximating the distribution of the Ipswich-Onslow microfloral province (Olsen and Galton, 1984). North of this was a tropical zone dominated by cycadophytes such as *Zamites*, and conifers such as *Pagiophyllum*. There was also a northern boreal province dominated by the pteridosperm *Lepidopteris*, dipteraceous ferns, and tree ferns (Dobruskina, 1988, 1993; Harris, 1931). Both the southern Gondwanan assemblage and the northern boreal province were associated with extensive coal-forming environments. A band of coal-forming environments was also associated with the tropical province, but was very tightly restricted to within a few degrees of the Pangean equator.

Terrestrial tetrapod communities seem, at least in part, to have followed the plant communities. Southern higher-latitude communities, associated with drab-colored sediments, were dominated by synapsids, at least in the early Late Triassic, and at the southern polar regions amphibians seem to been dominant. A similar synapsid-rich community was also present in proximity to the equator, but otherwise the tropical regions had, by the Late Triassic, become strikingly archosaur-dominated, with large amphibians represented almost exclusively by metoposaurs. This tropical tetrapod province overlaps the Gondwanan *Dicroidium*-dominated province on the Indian plate; hence the tetrapod and plant communities were not completely parallel. Triassic southern boreal tetrapod assemblages again seem to have been dominated by some of the same archosaurs as in the tropical regions; however, amphibians, which included the bizarre plagiosaurs, were far more diverse, No faunas are known from the Late Triassic for northern boreal and polar regions.

The lack of time control at the appropriate level of resolution outside of the central Pangean rifting zone, in addition to significant sampling gaps, particularly in the Norian and Rhaetian, precludes detailed knowledge of how these provinces changed, although 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 became more abundant, diverse and larger through the Triassic, with the moderate- to large-sized herbivorous prosauropod dinosaurs becoming common in the later Triassic (Norian and Rhaetian) at the boundaries between the tropical and boreal regions, and perhaps at higher latitudes, but remained virtually excluded from the lower latitudes. The provinciality and within-habitat diversity led to a very high-diversity global terrestrial biota, which is only now being appreciated (Anderson et al., 1986).

The Early Jurassic global biota was much more stereotyped. Most floral provinciality was gone, with the *Dicroidium-Thinfieldia* complex being completely eliminated. Conifers, especially the now-extinct Cheirolepidiaceae (*Corollina*- producers) were extraordinarily dominant in the tropics, a pattern that would continue until the mid-Cretaceous (Watson, 1988). A northern boreal province persisted, with infrequent cheirolepidiaceous conifers, but it was dominated by different groups (e.g.

Thaumatopteris) (Harris, 1931). The boreal southern areas had much less abundant cheirolepidiaceous conifers.

However, the tetrapod communities, at least at the beginning of the Early Jurassic, appear to have been virtually cosmopolitan, even at very low taxonomic levels (Shubin and Sues, 1991). Prosauropods and large theropods (larger than any in the Triassic) seem to have achieved nearly global distribution, along with crocodylomorphs and several other diapsid groups, with the same genera being reported from Arizona, southern Africa, Nova Scotia and China. Global and within-habitat diversity seems to have been much lower. There were no longer any synapsid-dominated communities; the only surviving members of this group were the tritylodonts, trithelodonts, and mammals, although again with nearly global distributions for several genera. Large amphibians were completely restricted to higher latitudes and had very low diversity. Most critically, non-ornithodiran (i.e. non-dinosaurs and pterosaurs) and non-crocodylomorph archosaurs were 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 (Olsen et al., 1987), making this mass extinction, at least as far as tetrapods are concerned, considerably larger that that at the Cretaceous-Tertiary 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 in the Newark, Fundy, and Argana basins to have occurred over less than 20 ky, and probably actually much less (Fowell, 1993; Fowell and Olsen, 1993; Fowell et al., 1994; Fowell and Traverse, 1995; Olsen et al., 2000a, 2002b,c), as it occurs within a single Van Houten cycle. A very similar rate of change evidently affected tetrapods, based mainly on Newark basin tetrapod footprint assemblages (as described above), although augmented with data from other Newark Supergroup basins (Figures 10, 11). This change is consistent with the much less intensely-sampled skeletal data.

In the Newark basin, the floral and faunal changes are directly associated with the fern spike and a newly-discovered iridium anomaly (Olsen et al., 2001b,c). The floral and faunal pattern (with the exception of the survival of the non-avian ornithodirans) and the associated iridium anomaly is strikingly similar to the pattern seen at the K-T boundary in the North American Western Interior (e.g. Tschudy et al., 1984), 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 (Badjukov, et al., 1987; Bice et al., 1992; Dietz, 1986; Olsen et al., 1987, 1990; Rampino and Caldeira, 1993).

However, 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, but always with an intervening small thickness of Jurassic strata. A possible causal link is difficult to ignore, given a similar (although less precisely timed) coincidence between the Deccan Traps and the K-T boundary and the Siberian Traps and the Permo-Triassic boundary (Rampino and Caldeira, 1993). The three largest Phanerozoic mass-extinctions are evidently very close in time to the three largest Phanerozoic flood basalt provinces, and all three have at least some evidence of asteroid impacts. A mechanism linking impacts with flood basalts has been proposed (e.g. Boslough et al., 1996), but the energetics are difficult to reconcile with the observations and the models (Melosh, 2000). Nonetheless, it seems plausible that a massive impact might be able to concentrate the effusive rate of a distant flood basalt province that was close to eruption; however, this topic has yet to be explored quantitatively.

At this point we can paint a speculative picture of what the Triassic-Jurassic transition may have been like, given present data (see summary; Figure 12). Biotic diversity was rising through the Late Triassic, but this increase was terminated by the impact of one or more asteroids or comets (e.g. Spray et al., 1998). As with the K-T scenario, continental biotas were initially affected by reduced sunlight and the attendant cold for a period of months, followed, in the case of the Triassic-Jurassic boundary at least, by a significant time of elevated CO_2 (McElwain, et al., 1999), leading to a rise in global temperatures. The massive ecological disruption was initially caused by the physical effects of the impact and then the cold, but these were then exacerbated by the rise in temperature, in turn probably associated with a great increase in the incidence of lightning-induced fire. This situation could only have been made worse by the succeeding CAMP flood basalt episode. The long term disruption allowed only rapidly-growing spore-dispersed plants - largely ferns - to populate the tropical regions over the next hundreds to thousands of years. The surviving dinosaurs may have all been small forms, but within 10 ky, theropod dinosaurs became considerable larger than any that had existed during the Triassic. The massive and sustained ecological disruption led to the extinction of many tetrapod families that were presumably dinosaurian competitors, and only afterward did the familiar dinosaur-dominated communities arise that would last for the next 135 million years.

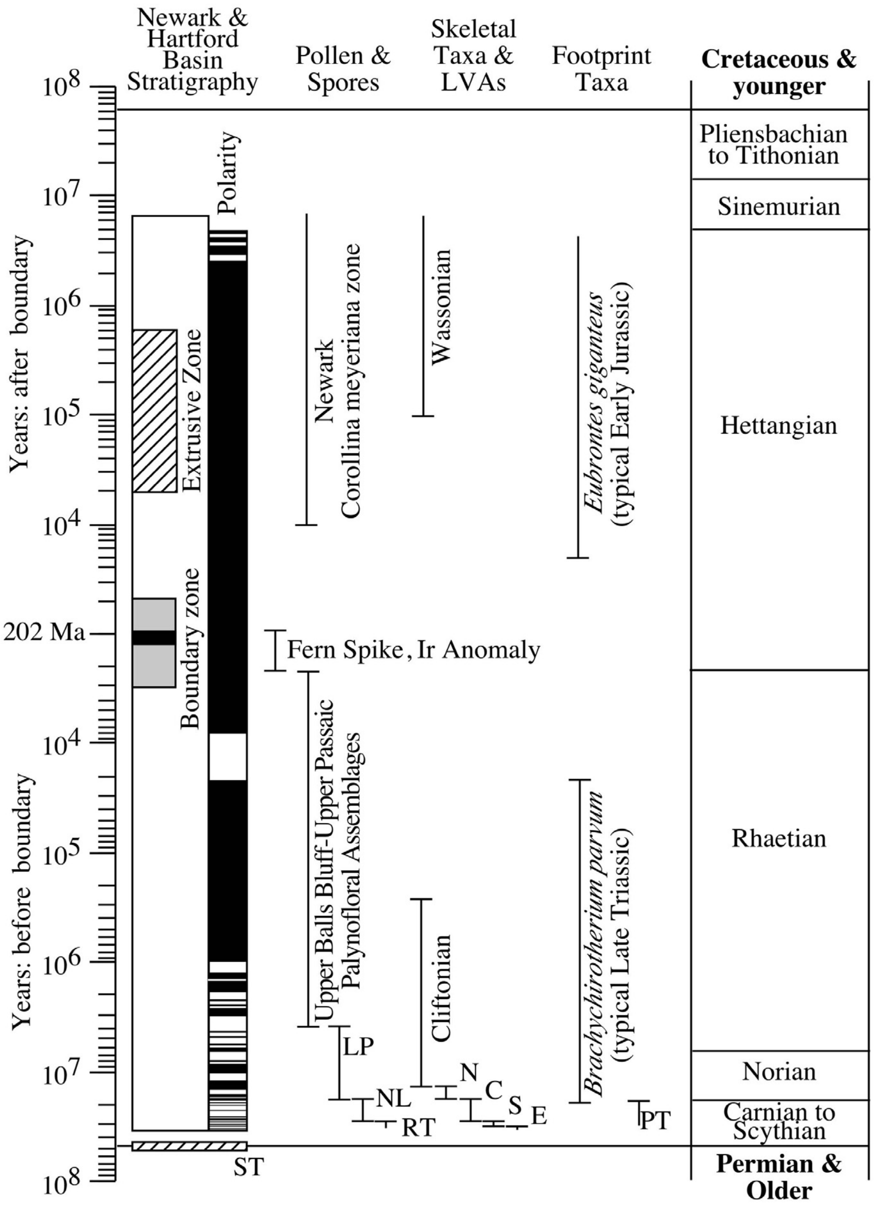

Figure 12. Summary of major physical and biotic events around the Triassic-Jurassic boundary plotted on a logarithmic scale (from Olsen et al., 2002c). LVAs are Land Vertebrate Ages of Huber and Lucas, 1997 and Lucas and Huber (2002): N, Neshanician; C, Conewagian; S, Sanfordian; and E, Economian. Pollen and spore zones are from Cornet (1977) and Cornet and Olsen (1985): LP, Lower Passaic Heidlersburg; NL, New Oxford, Lockatong; RT, Richmond Taylorsville. Footprint distribution; PT, range of the Pekin-type footprint assemblages. Note that the extrusive zone consists of lava flow formations interbedded with fossiliferous and cyclical sedimentary strata, with the latter interpreted as representing nearly all of the time shown. ST indicates the position of the Permo-Triassic Siberian Traps.

FIELD TRIP AND ROAD LOG

The field trip road log is focused around the present and ancestral route of the Hudson River (Johnson, 1931; Lovegreen, 1974; Stanford, 1993) (Figure 13) in the northeastern Newark rift basin, and present lower Hudson Valley. The road log begins and ends at Lamont Doherty Earth Observatory (LDEO), Palisades, New York, and together the 8 stops span most of the section in the northern Newark basin (Figure 14).

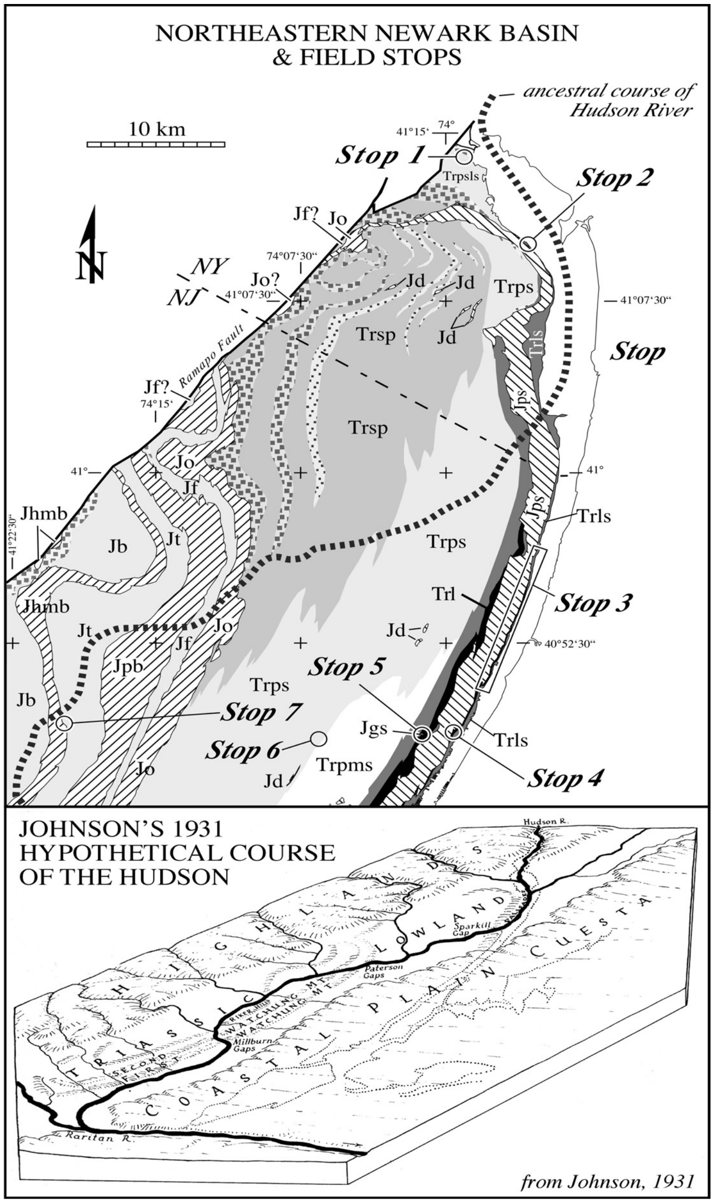

Figure 13. **A**, Northern Newark basin and ancestral course of the Hudson River (based on Johnson, 1931) with field trip route stops (see Figure 7 for key of lithostratigraphic units); **B**, late Cenozoic, pre-Holocene hypothetical course of the Hudson with assumed physiography (from Johnson, 1931).

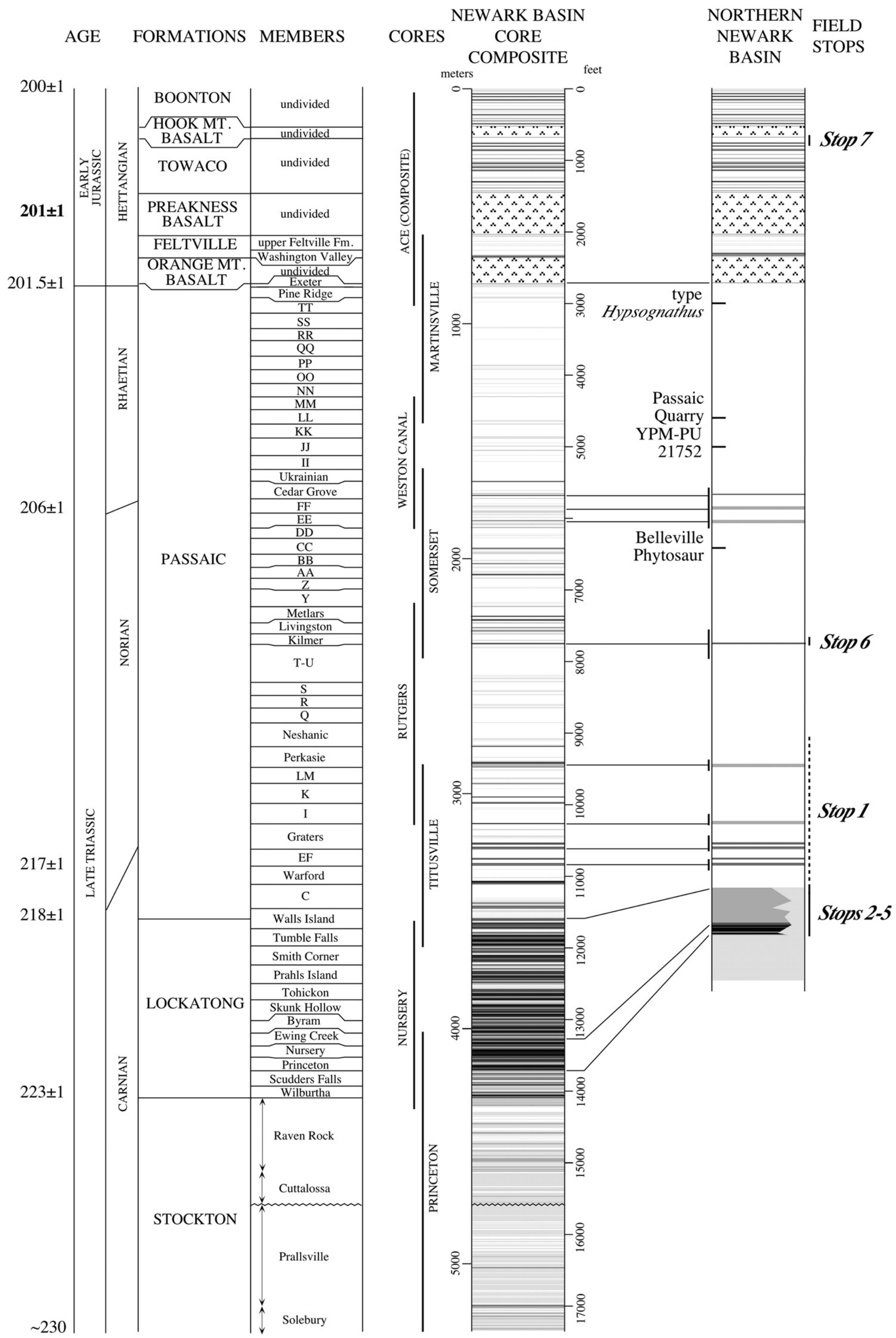

Figure 14. Newark basin section from the NBCP cores of the central Newark basin (left) compared to the stratigraphy of the northern Newark basin with field trips stops. See Figure 4 for key to lithologies.

0.0 mi. Leave entrance to LDEO, turn right and proceed north on Rt. 9W along the strike of the Palisade sill.

0.9 mi. Turn left (west) on Oak Tree Road and drive down the dip slope of the Palisade sill.

1.8 mi. Outcrops of diabase and hornfels of Lockatong-like facies.

2.3 mi. Crossing buried valley of ancestral (Miocene-Pleistocene) Hudson River.

2.6 mi. Turn right (north) onto Route 303.

7.3 mi. On right is the Blauvelt footprint site discovered in 1972 by PEO and Robert F. Salvia. Site consists of the excavated dip slope of gray, tan, pink, purple, and red mudstones and sandstones of the Stockton Formation equivalent of the Lockatong Formation.

Tracks found include a slab of tridactyl footprints often attributed (incorrectly we believe) to the ceratosaurian theropod dinosaur *Coelophysis* (e.g. Fisher, 1981), and isolated tridactyl tracks (Figures 15, 16). These tracks are rather broad and tulip-shaped suggestive of large *Atreipus* (see mileage 34.8 and Stop 6), the early ornithischian dinosaur ichnite. However definitive manus impressions are lacking, and they tend to be broader than most *Atreipus*. They could belong to a new form, but because of their overall poor preservation, they remain indeterminate.

Other footprint forms found are largely indeterminate but include indeterminate forms that are probably poorly preserved examples of small *Brachychirotherium* as well as an example of *Rhynchosauroides* cf. *R. hyperbates* (Figure 15). Indeterminate phytosaur teeth and bone scraps occur in the footprint-bearing beds.

On the south side of the exposures are greenish and tan mudstones with abundant and often large roots and tree trunk casts suggestive a strongly vegetated surface (Figure 15).

7.8 mi. Outcrop on right is Palisade sill that has moved considerably higher in the section to the Stockton-Passaic formational boundary.

8.8 mi. Pass Lone Star quarry on left in a large apophysis of the Palisade sill.

9.1 mi. Palisade sill moves lower in section in this area.

13.7 mi. Merge with Route 9 W on dip slope of Palisade sill.

14.2 mi. Long Clove Quarry in Palisade sill on left.

14.4 mi. Pass through small fault gap to the front of the questa of the Palisade sill.

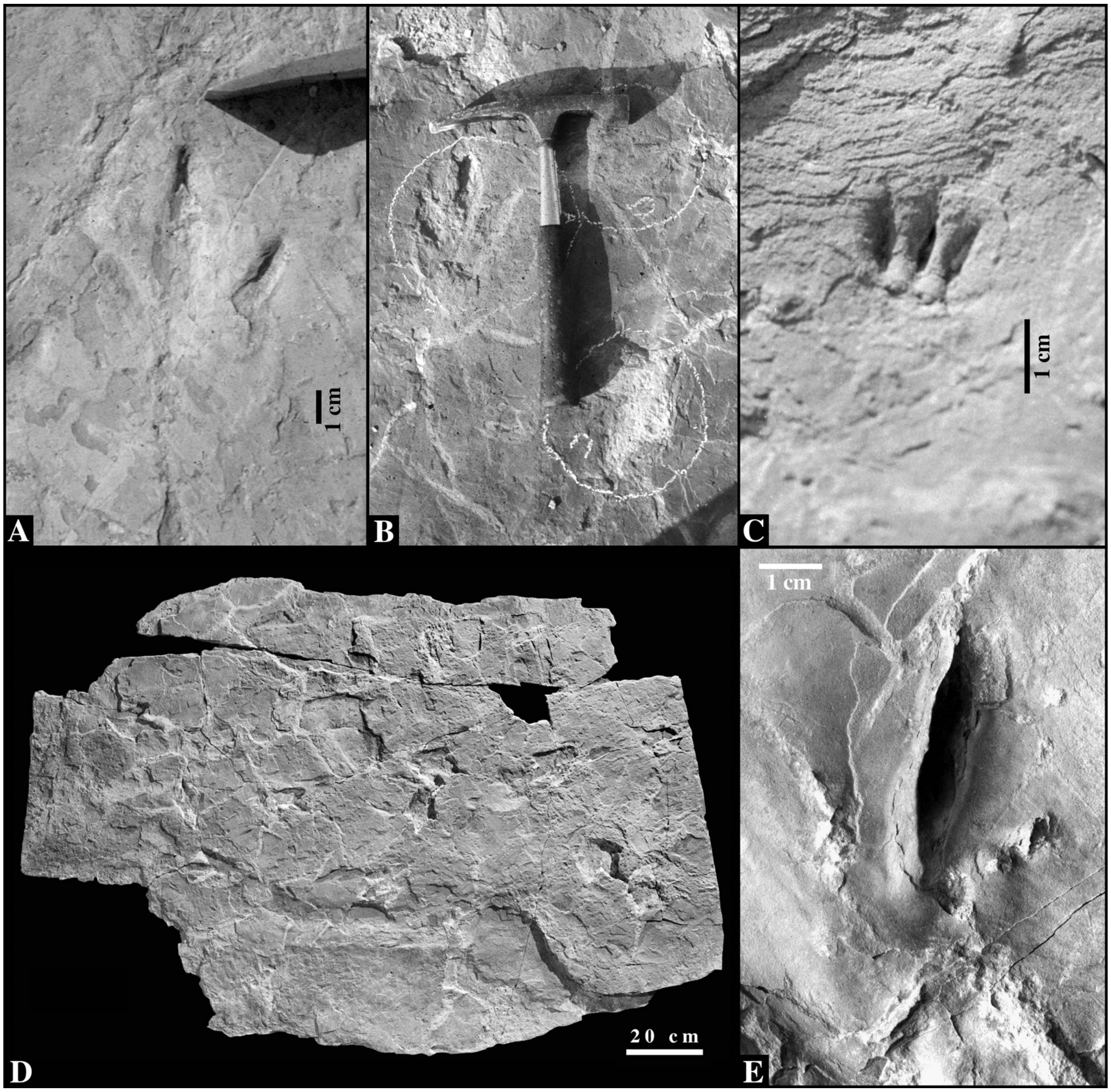

Figure 15. Footprints from the Blauvelt and Upper Nyack track localities: A, indeterminate isolated pes impression in situ (uncollected), from Blauvelt, New York; B, indeterminate tracks as found of main slab now at the New York State Museum, Albany (from Blauvelt, New York); C, leptodactylus quadrupedal track, probably *Brachychirotherium*, from Blauvelt, New York; **D**, indeterminate dinosaur tracks (possibly *Atreipus*) on main slab after collection, now at the New York State Museum, Albany (Blauvelt, New York); leptodactylus *Grallator* cf. *G. parallelus* footprint, Upper Nyack, New York.

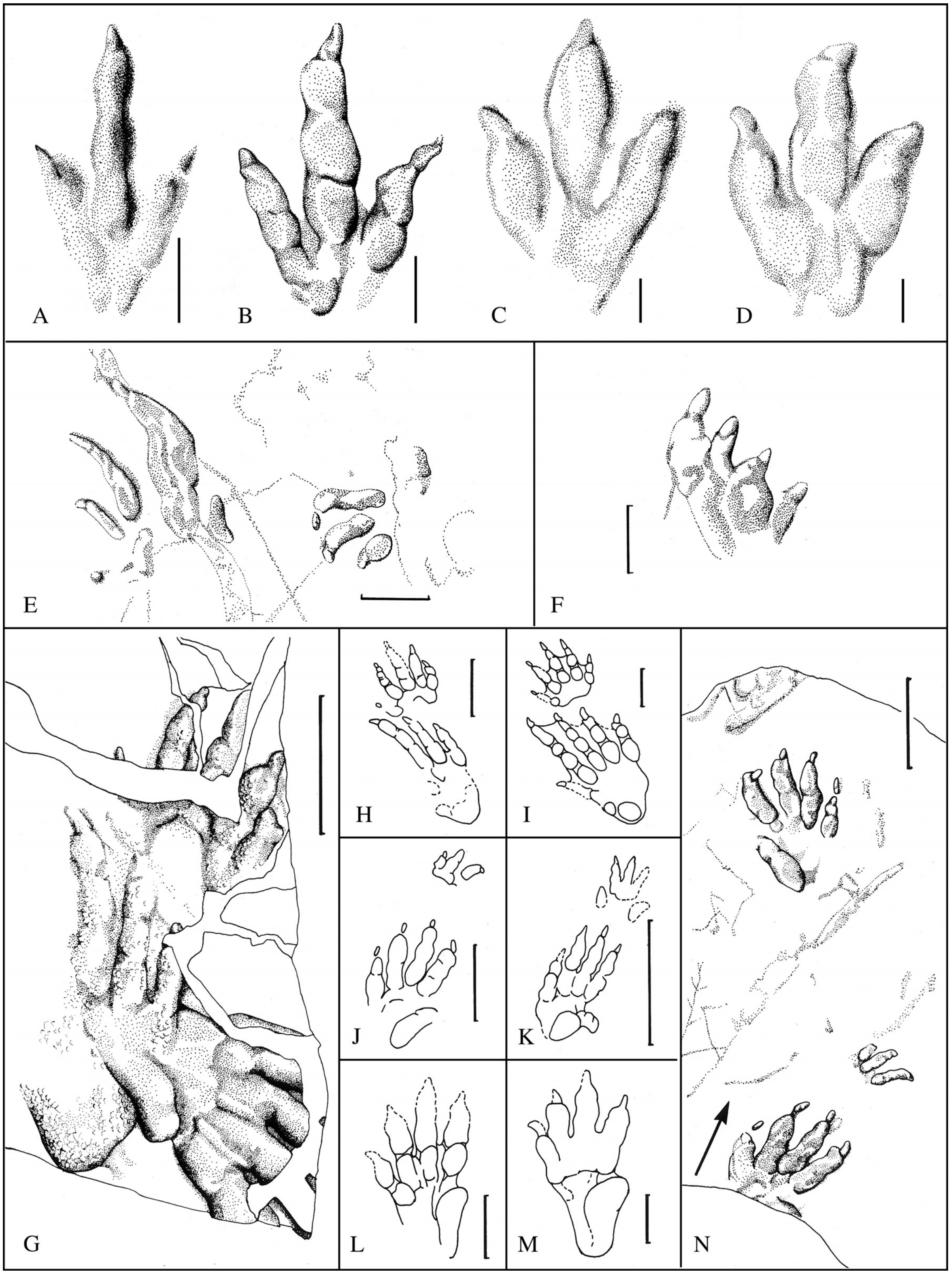
A
B
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Figure 16. Drawings of footprints from the Stockton Formation of New York: **A**, *Grallator* cf. *G. parallelus* from Upper Nyack (in collection of D. Fisher - see Figure 15D); **B**, Grallator sp., from Stop 2, Haverstraw, New York (specimen lost); **C-D**, indeterminate dinosauria track, possibly Atreipus on main slab after collection, now at the New York State Museum, Albany (from Blauvelt, New York); **E**, *Rhynchosauroides* cf. *R. hyperbates*, from Blauvelt, New York (YPM 7733); **F**, *Rhynchosauroides* cf. *R. hyperbates*, from Stop 2, Haverstraw, New York (YPM 8265); **G**, *Apatopus lineatus* and *Brachychirotherium* cf. *B. eyermani* from from Stop 2, Haverstraw, New York (YPM 7731); **H**, outline drawing of Apatopus lineatus shown in **G**; **I**, outline drawing of *Apatopus lineatus* from Baird (1957) see Figure 25; **J**, outline drawing of composite of manus-pes sets of *Brachychirotherium* cf. *B. eyermani* from N; **K**, *Chriotherium lulli* from Baird (1954); **L**, outline drawing of *Brachychirotherium* cf. *B. eyermani* based on **G**; **M**, *Brachychirotherium eyermani* from Baird (1957); **N**, *Brachychirotherium* cf. *B. eyermani* from Stop 2, Haverstraw, New York (YPM 8262), see Figure 25. Scale is 2 cm in A-D, 1 cm in E-F, 5 cm in G-N.

14.5 mi.	Outcrops on left are of red sandstones of Stockton facies. As we travel north the contact with sill drops discordantly lower in the sedimentary section.
15.0 mi.	Cliff of Palisade sill. On the back of the escarpement is the Long Clove quarry in the sill. Crushed stone passes though a tunnel in the sill to the offloading docks on the right.
17.0 mi.	Strike ridge of Palisade sill curves strongly to the west.
18.9 mi.	Crossing Cedar Pond Brook.
19.0 mi.	Turn right on Lowland Hill Road.
19.2 mi.	Turn right onto into parking lot for Lowland Town Park and park.

Stop 1: Gorge of Cedar Pond Brook, Stony Point, New York.

Latitude and Longitude: 41°13.605', 073°59.079 ' to 41°13.677', 073°59.378
Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: ?lower Passaic Formation
Age: Late Carnian (early Late Triassic); ~220-223 Ma
Main Points:

1. NE terminus of Newark basin near onlap onto basement of TS III
2. Sediment-starved section with well-developed carbonate beds
3. Carbonates of ?lacustrine and pedogenic origin - local source
4. Should be ideal area for bone or egg preservation

5. Relevant to arguments about the Broad Terrane Hypothesis

Cedar Pond Brook flows from west to east cutting a gorge though a unique carbonate-rich facies of the Newark basin section at its northern terminus (Figures 17, 18). The western, coarse-grained part of the section was mentioned by Ratcliffe (1980) and described in outline (with thin sections) by Sanders (1974), but is otherwise virtually unstudied.

Conglomerates making up the basal beds of the local section outcrop to the east in a railroad cut within the Stony Point Battlefield Park (Figure 17). Basement here consists of metamorphic rocks bordering the Cortland Complex, which is locally reddened near the contact with the conglomerate. The contact itself is not exposed. According to Ratcliffe (1980), the exposed conglomerates contain clasts of Manhattan Schist and Ordovician Inwood Marble dolostone clasts, both clast types being derived very locally from the east and north. The section fines to the west, passing up-section into a cyclical sequence of red calcareous mudstones and sandstones and pink to gray limestones (Figures 19, 20).

Cycles have a mode about 1.5 m with a large amount of variation consist of a lower red silty mudstone with abundant *Scoyenia* burrows and root traces, passing upward into mudstone with carbonate nodules; these nodules often coalesce upward into a bed of pink to white massive limestone (Figure 20). The limestone contains thin (~2 mm) branching tubes that are most likely root traces, but sometimes also (apparently) ostracodes, identified in thin section by Sanders (1974). These biologic remains indicate that at least some of the limestones are of lacustrine origin, perhaps modified by pedogenic structures. Many of the mudstones and limestone beds have large (~1 m long, ~3 cm wide) root traces and most mudstones have densely branching thin root traces.

Strikingly absent from these outcrops are larger-scale fluvial units such as channels. However, also absent are any indications of Van Houten cycles, unless they are the limestone cycles themselves. This facies resembles no others in this part of the basin, although it does bear some similarity to the middle upper Passaic of the Jacksonwald syncline, where carbonate beds are well-developed (although not as well-developed as here). This suggests that this section represents a relatively dry phase of a McLaughlin cycle, probably in the lower Passaic Formation, in an area of the basin isolated from entry points of major rivers or streams.

Ratcliffe (1980) described the "Annsville Phyllite", present to the west on the hanging wall of the Ramapo fault system (here the Thiells splay). Sedimentary breccias of (?)Inwood Marble carbonate occur locally near the fault low in the section on the north side of the Cedar Pond Brook gorge. This indicates that there was indeed a local source of abundant carbonate, which probably accounts for the extreme development of limestone beds in this facies.

Recently, it has become clear that tetrapod remains are present and locally abundant, being well preserved at many levels within the Newark Supergroup in red massive sandy to silty mudstones which contain root traces and have variable development of carbonate nodules and caliches (Carter et al., 2001; Olsen et al., 2000b, 2001b; Sues et al., 2000). The abundance of carbonate helps to buffer bone dissolution in a pedogenic environment, and can allow otherwise very perishable vertebrate carbonate fossils - eggs - to be preserved. The association of pedogenic carbonate nodules (caliche or Kunkar) and tetrapod bone has been repeatedly noted elsewhere (e.g. Dodson et al.,

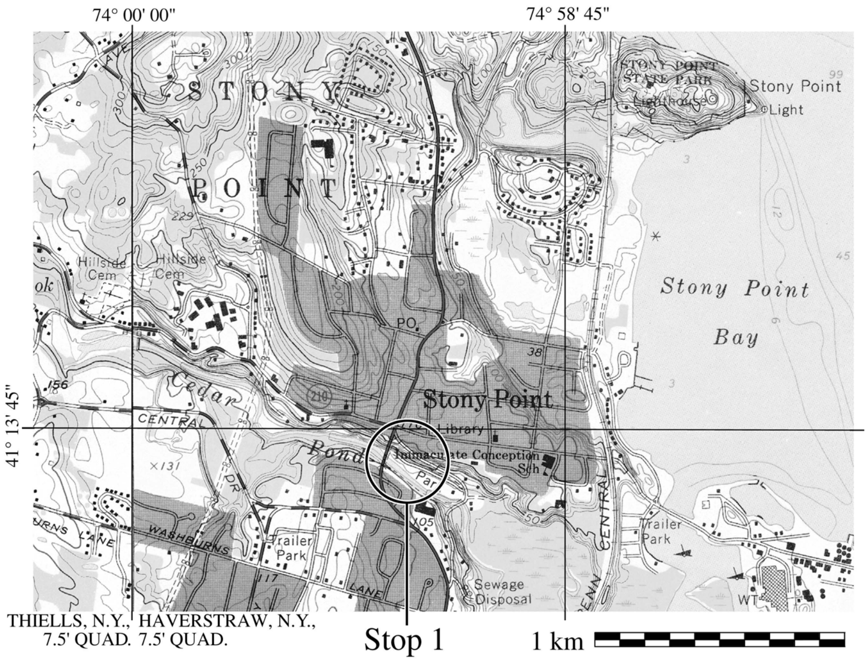

Figure 17. Location map Stop 1.

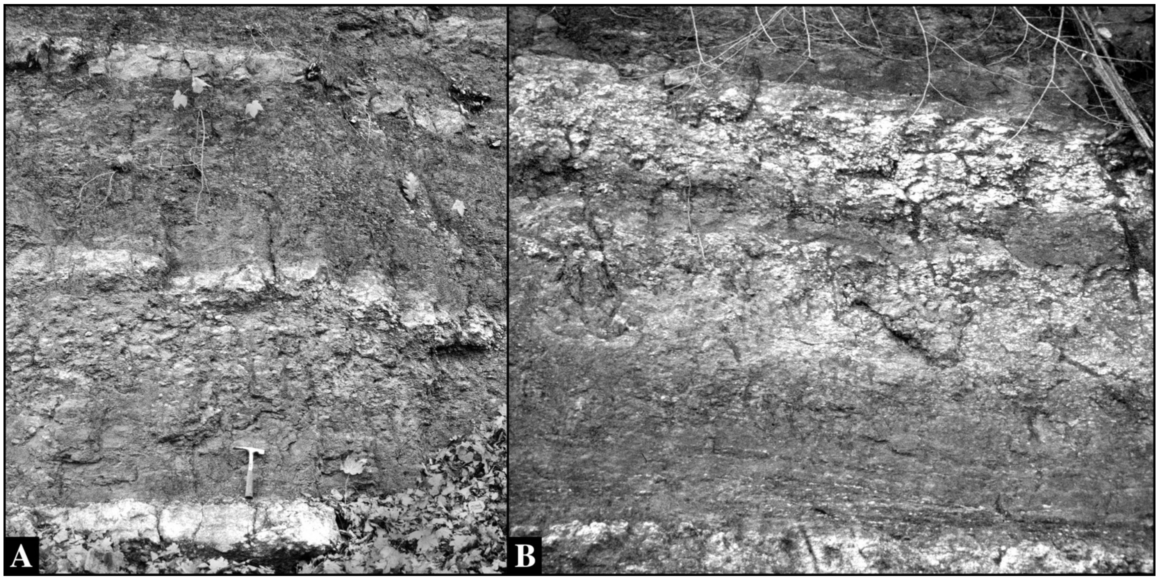

Figure 18. Photos of representative portions of the section at Stop 1: A, two complete successive carbonate-bearing cycles (from 17-20 m in Figure 19); B, two successive carbonate-bearing cycles of different thickness (25-29 m in Figure 19), note meter-scale root-traces (one very obvious at upper right).

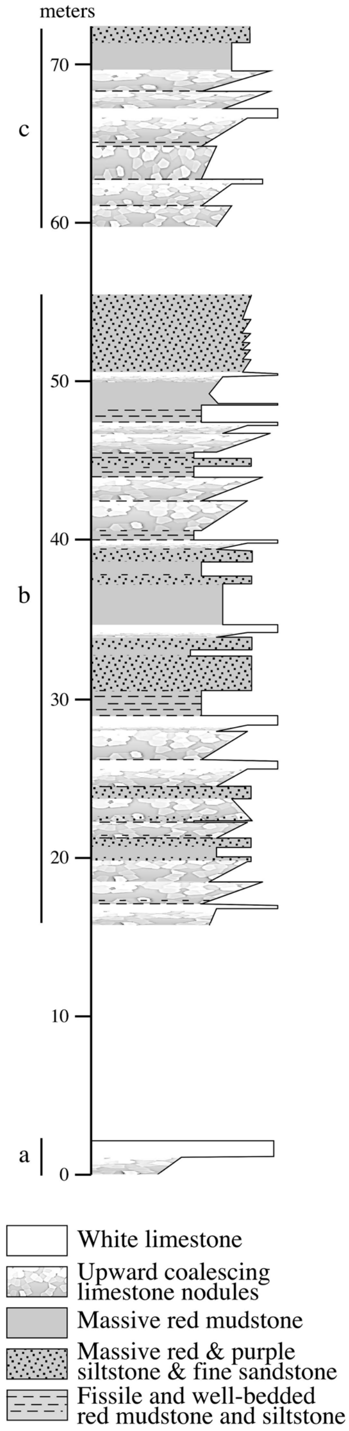

Figure 19. Stratigraphic section at Cedar Pond Brook: **a**, gully, north side of Longhill Town Park, latitude 41°13.692' N longitude 073°59.189' W; **b**, section on south bank of Cedar Pond Brook, south side of park and beneath bridge for Rt. 9W, from latitude 41°13.605' N longitude 073°59.079' W to latitude 41°13.674' N longitude 073°59.242' W; **c**, section west of bridge on slope to south of Cedar Pond Brook latitude 41°13.677' N longitude 073°59.378' W .

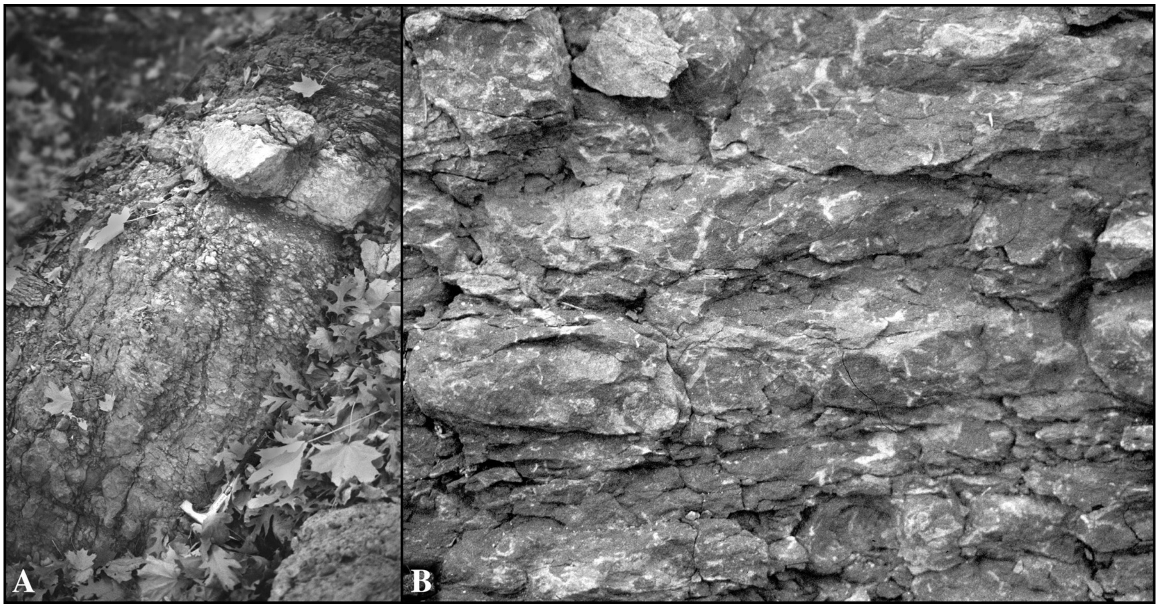

Figure 20. Carbonate cycle details: **A**, upward coalesing carbonate nodules in single cycle at 44 m in Figure 19; **B**, prevalent well-developed heavily rooted massive mudstone fabric (at 20 m in Figure19, image spans about 30 cm vertically).

1983). These outcrops should be ideal for bone preservation, but there has been little prospecting as of yet. Persistence is needed, however, because the tetrapod fossils tend to be nearly the same color as the carbonates, making it very difficult to locate.

This northeastern part of the Newark basin was crucial to Sanders (1960, 1963, 1974) arguments for the "Broad Terrane Hypothesis". This hypothesis was first proposed by I.C. Russell (1879, 1880), who argued that the Newark and Hartford half-graben basins were actually the western and eastern components of a giant full graben which had been post-depositionally uplifted in the middle and then deeply eroded (Figure 21). Sanders considered the northeastern terminus of the Newark basin to be a key area because it showed that this end of the basin was an artifact of post-deposition folding, indicated by the basement-parallel strike of the beds wrapping around to the west, towards the border fault. Sanders argued that there is no indication of onlap of progressively younger strata onto basement to the northeast; therefore the basin did not shallow in that direction, and the high between the basins did not exist at the time of deposition.

We argue that these outcrops favor exactly the opposite interpretation. There is no evidence at all that the sequence seen at Stops 1-4 is the basinward equivalent of the basal section (i.e. Stockton Formation) of the Newark basin. The facies is utterly unlike the local expression of the Stockton, and all the evidence (as seen in stops 2-4) points to a shoaling of the basin towards the north and east. In addition, the map pattern (7, 13) indicates rapid thinning of the Passaic Formation toward this area and dramatic changes in strike, both of which are consistent with the existence of a syndepositional basin high in the region between the Newark and Hartford basins.

However, this does not mean that there might not have been a sedimentary connection between the two basins. The Newark and Hartford basins are deeply eroded, and if TS III in eastern North America follows the pattern seen in the much less deeply eroded Moroccan basins, we should expect there to have been onlap of the younger parts of TS III over basement, eventually connecting the two basins. Strata of TS IV, particularly the basalt flows and thinned interflow units, may also have connected the basins (c.f. McHone, 1996). It is also quite likely that considerable amplification of the high between the two basins occurred postdepositionally as a consequence of late Early Jurassic to Middle Jurassic tectonic inversion. However, there is no evidence supporting the argument that the deepest part of the combined Newark-Hartford basin lay in the now-uplifted region between them, as proposed in Russell's and Sanders' versions of the Broad Terrane Hypothesis.

Go back to entrance of Lowland Town Park.

19.3 mi. Turn right back onto Lowland Hill Road.

19.5 mi. Turn left onto Rt 9W and head south.

23.2 mi. Turn left (east) onto Short Clove Road

23.4 mi. Turn right (south) onto Riverside Avenue.

24.2 mi. Park at south termination of Riverside Avenue in parking lot for Hook Mountain State Park of the Palisades Interstate Park.

Walk south along path about 1060 m looking for ruins on left.

Turn left at ruins and (carefully!) proceed down the rocky and vegetated slope to Stop 2.

Stop 2. West shore of Hudson River, Palisades Interstate Park, Haverstraw, New York.

Latitude and Longitude: 41°10.383'N. 073°56.097'W.
Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Stockton Formation
Age: Late Carnian (early Late Triassic); ?220 Ma
Main Points:

1. Stockton-like equivalent of Lockatong Formation at basin edge
2. Fluvial and ?lake margin facies of *wet* part of McLaughlin cycle
3. Multiple fossil-rich facies
4. Sampling of more terrestrial communities than usual for this time
5. Well-preserved footprints in unusual settings
6. Relatively abundant bones in tan quartz-pebble conglomerate

Abundant outcrops and exposures below the Palisade sill extend from Haverstraw, New York south to Hoboken, New Jersey allowing a close look at the facies changes along-strike progressing from mostly-fluvial environments in the northeast to the mostly lacustrine cyclical facies in the southwest. Outcrops along the west shore of the Hudson River in this segment of the Palisades Interstate Park consist mostly of various fluvial facies with some hints of lacustrine influence. This site consists of exposures in a small abandoned quarry and river-side outcrops of a ~17 m thick section of very heterogeneous clastic rocks, including tan quartz-pebble conglomerates, pink and red sandstones, and purple and red mudstones and siltstones (Figures 22, 23, 24).

Evidence for this section being the along-strike equivalent of the lower part of the Lockatong (probably the Nursery or Ewing Creek member) consists primarily of the apparent continuity of strike direction from unquestionable Lockatong outcrops to the south of this region. If there is some hanging wall onlap of younger strata onto basement in this direction - and there is a hint of this - these outcrops would still likely be part of the Lockatong rather than lower in the section. In addition, the facies change northwards along-strike from the Lockatong is slow, consistent, and significantly different from the lateral change within the Passaic Formation in the same region that trends towards exclusively red conglomerates.

The abundance of tan, pink, and purple strata at this section (Figure 24) suggests prolonged water saturation of the sediments prior to lithification, and, together with the relatively muted pedogenic influences, suggests deposition during a relatively wet episode. The thickness scale of the section showing these features suggests perhaps a wet phase of a 404 ky cycle as is also expressed in the Lockatong Formation to the south (e.g. Stops 4 – 6). However, it is important to note that we have no direct knowledge of the scale of depositional relief (e.g. of marginal deltas), nor is there a clear indication of a hierarchy of cycles, so this interpretation has to be regarded as tentative.

What makes this site particularly interesting is the relative abundance of tetrapod fossils in virtually all lithologies. Most of the fossils are found right at the Hudson shoreline, where rubble piles from the old quarry are eroding into the river, providing clean and fresh rock faces for examination. It is well worth pulling material directly from the eroding rubble piles, as well as turning over slabs in the river itself.

The lithology most consistently producing bones is a tan quartz-pebble conglomerate. Bones and teeth are white in this matrix and comparatively easy to see. Blocks of this material should be broken up to hand-size pieces to reveal fresh faces before being discarded. Thus far, a small partial (?)skull (as yet unprepared; Figure 25), an amphibian dermal bone, numerous (?)phytosaur teeth, and many unidentified bone and teeth fragments have been found. Red and purple siltstones and sandstones have also yielded white bone and tooth scraps, so these lithologies should also be carefully examined.

Reptile footprints are surprising common at this site and occur in a variety of lithologies, showing nearly the full range of footprint preservational styles (Figure 26). Perhaps the most unusual style of preservation is in a red to dark reddish-purple medium-grained sandstone, in which the tracks are preserved as sometimes high-relief natural casts on the underside of beds, frequently preserving skin impressions and other exceptional details. The tracks are actually impressions in a thin massive silty claystone which crumbles when the overlying sandstone is separated. Tracks are also found as

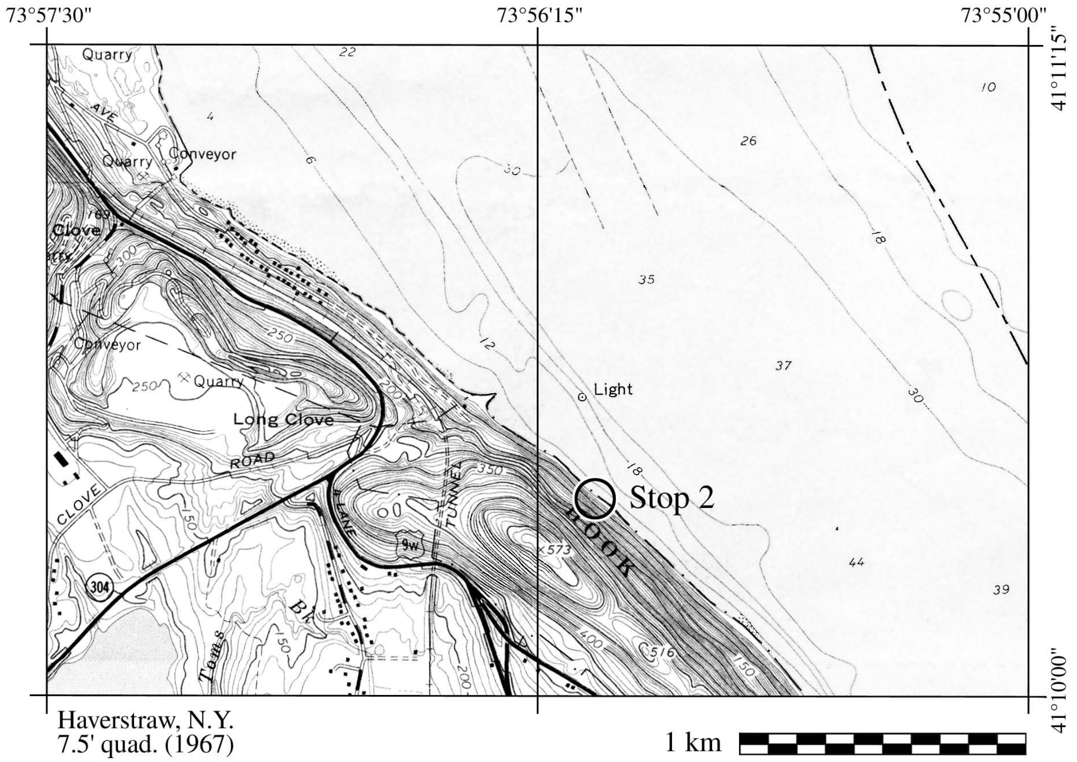

Figure 22. Stop 2 site map.

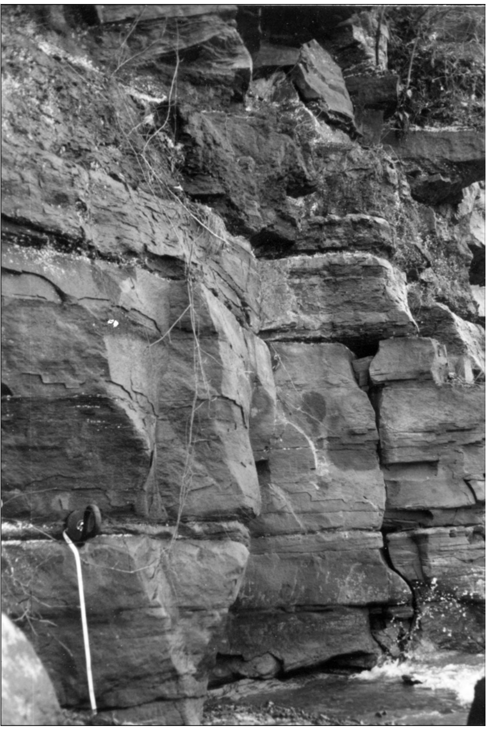

Figure 23. Photograph of outcrops looking north at waters edge at Stop 2 (latitude 41°10.394' N longitude 073°56.088 W). Length of exposed tape measure is 1.5 m.

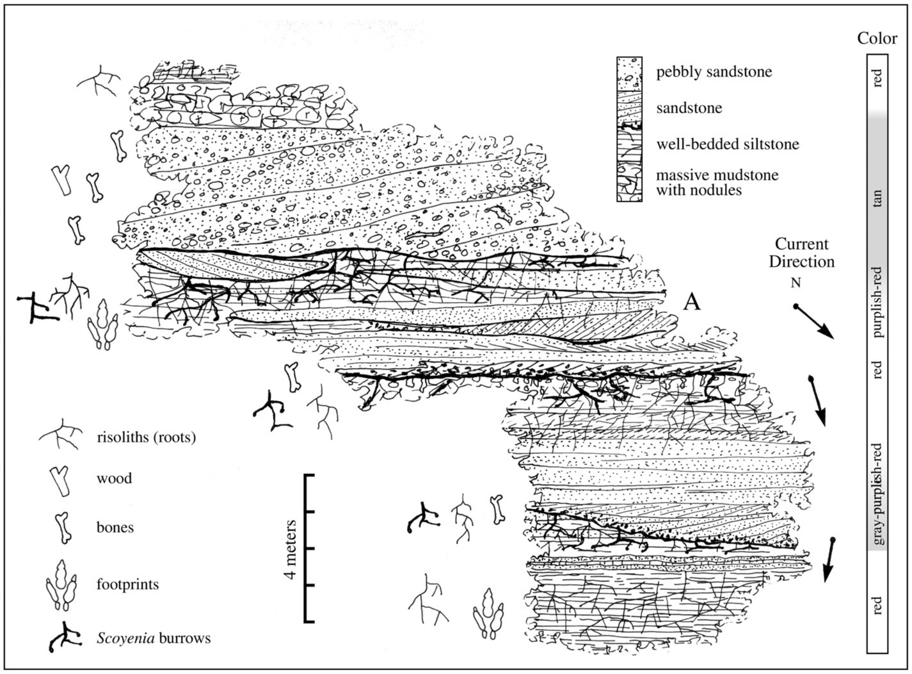

Figure 24. Measured section at Stop 2, Haverstraw, New York from the old quarry to the river (from latitude 41°10.379' N longitude 073°56.097' W to latitude 41°10.396' N longitude 073°56.088 W). Vertical exageration about 3 x.

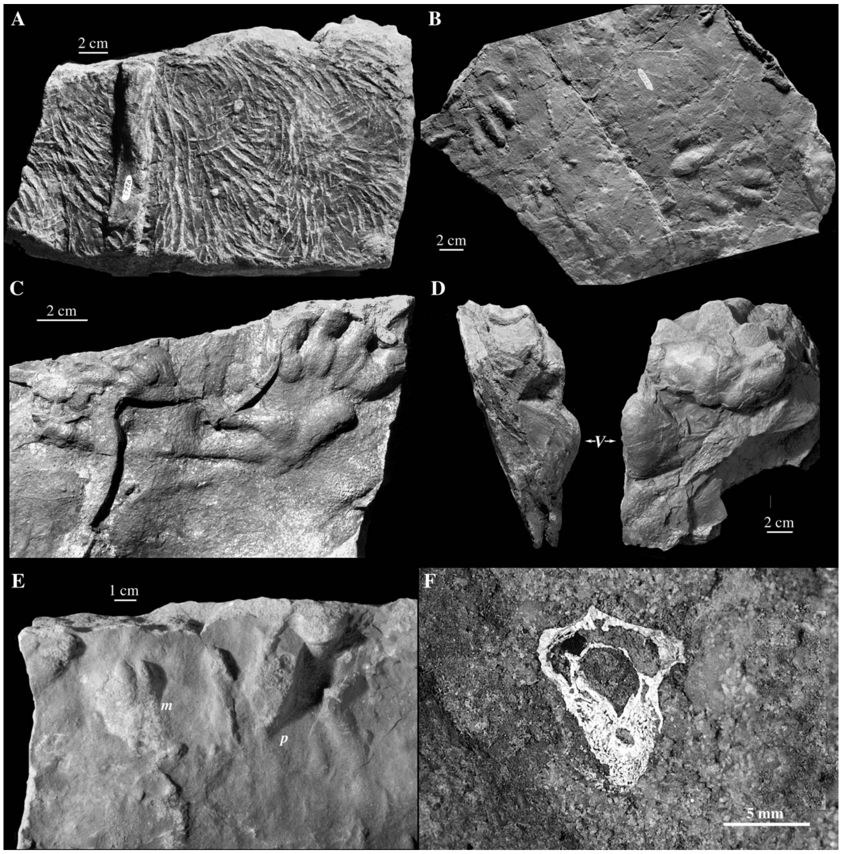

Figure 25. Fossils from Stop 2, Haverstraw, New York: **A**, natural cast of scratch marks probably made by the animal that produced *Rhynchosauroides hyperbates* (YPM 8263); **B**, natural cast of partial trackway of *Brachychirotherium* cf. *B. eyermani* (YPM 8262); **C**, natual cast of manus-pes set of *Apatopus lineatus* and partial pes of *Brachychirotherium* cf. *B. eyermani* (YPM 7731); **D**, very deep natural cast of *Brachychirotherium* cf. *B. parvum* (AMNH uncataloged), V indicate digit V (five); **E**, natural cast of poor manus (m) and pes (p) set of ?*Atreipus* sp. (YPM 8553); F, partial tetrapod skull (AMNH uncataloged).

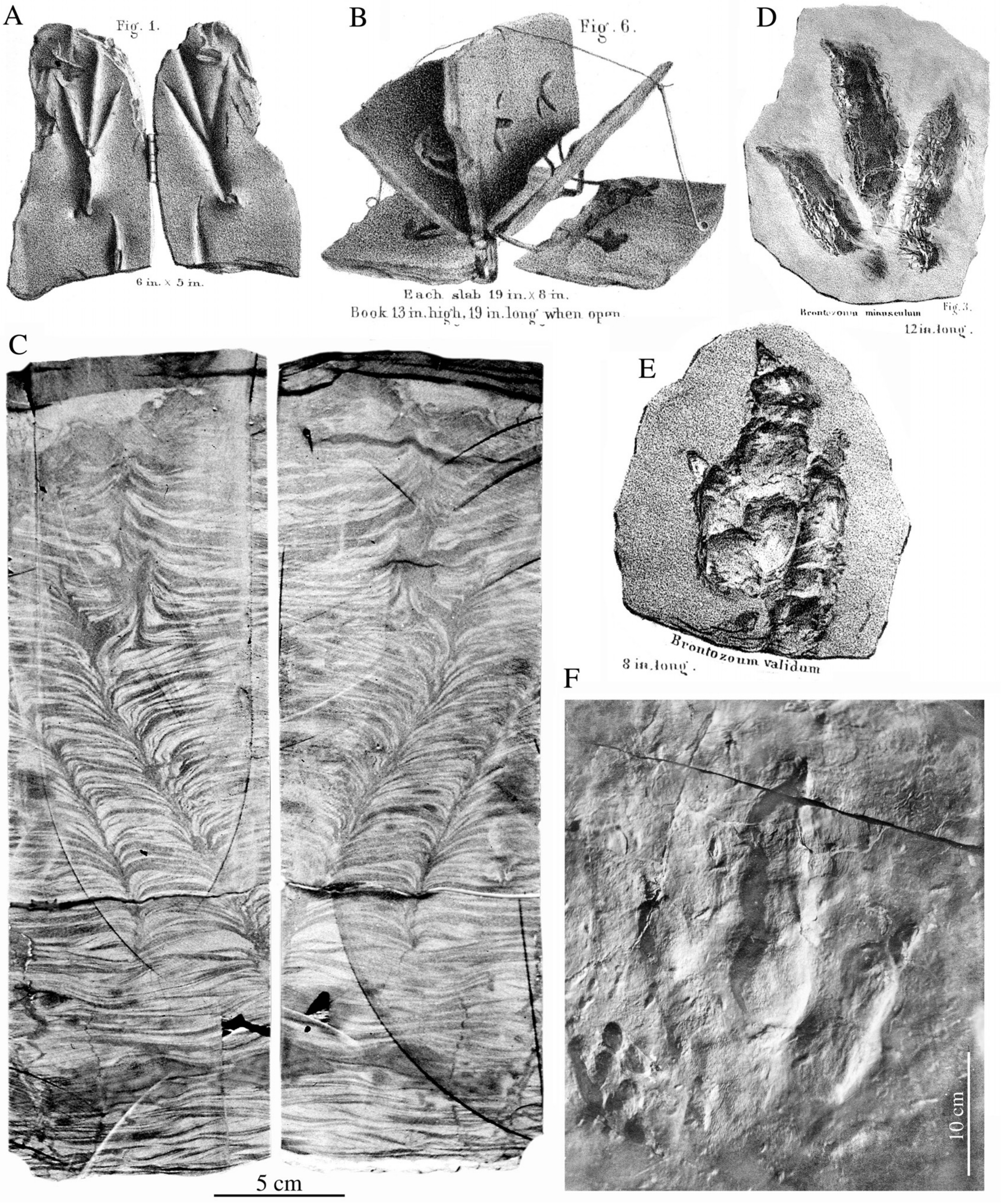

Figure 26. Footprint preservational styles: **A**, leptodactylus form labeled *Triaenopus leptodactylus* (AC 27/9 from Hitchcock, 1956, Plate LII, fig. 2); **B**, another classic leptodactylus form making up a "stony volume" in which the track is impressed though many layers given the name of *Platypterna varica* (AC 27/4 from Hitchcock, 1956, Plate LII, fig. 6); **C**, cross section of leptodactylus track from a core (Park River core FD 12T, 44 ft) from the Portland Formation, Hartford, Connecticut (downwardly merging laminae were produced as the foot was implanted and upwardly merging laminae were produced as the foot was withdrawn); **D**, natural cast of an underprint type fooptrint in which the actual surface in contact with the foot was a centimeter or so above the layer that spit open, labelled *Brontozoum minusculum* (from Hitchcock, 1956, Plate LVII, fig. 2); **E**, natural cast of a normal track in which the surface that visible is the surface that was in contact with the foot, labelled *Brontozoum validum* (from Hitchcock, 1956, Plate LVII, fig. 3); **F**, natural mould of a normal track in which the surface that visible is the surface that was in contact with the foot as is made obvious by the presence of the impression of skin on parts of the track, labeled *Brontozoum minusculum* (from Dean, 1861, Plate 16).

lower-relief natural casts and impressions in flaggy sandstones and siltstones, as faint underprints, and as leptodactylous forms (Figures 25, 26). The group name *Leptodactyli* ("thin-toed") was introduced by Edward Hitchcock (1836) for what he regarded as a major subdivision of tracks. In fact such tracks are extremely interesting traces representing one end-member of preservational style, that record the implantation and extraction of a foot in deep (relative to the foot size), soft, usually ripple cross-laminated silt or very fine sandstone. The substrate must have been water-saturated at the time of impression, and probably not bound by micro-organisms such as algae. Gatesy et al. (1999) was (to our knowledge) the first to recognize the true nature of these traces and to extract useful information about trackmaker locomotion from them. The hallmarks of the leptodactylous style of impression is that the "soles" of the toes appear sharply pointed or creased in cross-section, the impression passes through many layers, and on each layer the track has a different shape. This style of track can be extremely abundant where ripple cross-laminated siltstones are present, and while they have great potential to understand locomotory mechanics, they provide little information on the identity of the trackmaker, and sometimes lead to spurious interpretations (e.g. the supposed presence of feathers at the back of the feet).

Thus far, *Rhynchosauroides* cf. *R. hyperbates*, *Apatopus lineatus*, *Brachychirotherium* cf. *B. eyermani*, and cf. *Atreipus* and other indeterminate dinosaurian tracks have been found at this locality, which is one of the oldest footprint assemblages in the Newark basin. Associated with the *Rhynchosauroides* cf. *R. hyperbates* are crisscrossing scratch marks of the appropriate size to have been made by the same trackmaker (Figure 25). Similar scratch marks arranged in crescent-shaped arrays occur associated with *Rhynchosauroides* at other localities (Olsen et al., 1989), and have even been interpreted to be the tracks of a hairy cynodont (Ellenberger, 1976). These scratch traces are almost certainly all foraging traces of reptiles. A striking feature of this and all of the older track localities in the Newark Supergroup (see mileage 34.8 and Stop 6) is that dinosaurian tracks are not common and all are relatively small.

Lockatong Formation fossil assemblages tend to be very stereotyped, almost entirely biased toward preservation of aquatic forms (unsurprising given the dominance of lacustrine facies). Thus this type of assemblage, from fluvial facies (i.e. Stockton Formation) of Lockatong age , is very important, in that it provides a sampling of a more terrestrial assemblage for Lockatong time. Careful further prospecting at this site and others along the Hudson, should provide much more information.

Retrace route back to 9W.

25.3 mi. Turn left onto Route 9W, going south.

26.8 mi. Intersection with Rt. 303, proceed on 9W south.

27.2 mi. Tunnel for Penn Central Railroad. Western portal has outcrops of tans sandstones and dark gray hornfels. Contact with sill is strongly discordant and was figured by Kümmel (1899).

30.8 mi. Cut through discordant limb of Palisade sill.

31.3 mi. Exposures behind Volkswagen repair shop are of tan, gray, and red sandstone. Reptile tracks occur in well-bedded gray siltstones. Tracks include *Grallator* cf. *G. paralellum* (sensu Olsen et al, 1999) and *Brachychiroptherium* sp. (Figure 15). Tan sandstone beds with shale chips and carbonate bleb lags have scales of *Turseodus* and indeterminate small tetrapod bones and teeth.

31.5 mi. Turn left onto Old Mountain Road.

32.2 mi. Turn left onto Castle Heights Road,

32.5 mi. Turn right onto Broadway, heading south. To north is Hook Mountain State Park with outcrops of the Palisade sill and underlying Stockton Formation briefly described by Sanders (1974).

33.3 mi. Turn left onto Depew Road.

33.35 mi. Turn right onto Piermont Avenue and head south.

34.4 mi. Overpass for New York State Thruway and west portal of the Tappan Zee bridge. Borings for the bridge identified the Stockton-basement contact in the Hudson (Figures 7, 13) (Sanders, 1974).

34.8 mi. Brownstone Quarries, Grandview, New York

A string of small- to medium-sized quarries were developed during the 19th and early 20th centuries in red clastics below the Palisade sill, from just south of the present position of the west ramp for the Tappan Zee Bridge in South Nyack, to northern Piermont. These quarries all seem to have exploited the same facies of red fluvial sandstone and mudstone. Much of this distinctive bright red-orange-brown sandstone was used for the construction of buildings in Nyack and homes in Grandview. Most of these quarries now contain private homes.

The sections exposed in these quarries consists of fluvial sequences, much of which are heavily bioturbated by roots and burrows. Several moderate-sized channels are exposed. The abundance of pedogenic structures, and the lack of drab colored beds indicative of long-term water saturation, suggest that this facies is within a dry phase of a 404 ky (or longer) cycle. In support of this, the belt of red clastics progressively rises in elevation to the south and is underlain by a bench of drab coarser-grained clastics that also rises in elevation southwards to central Piermont, where it is exposed along River Road and Ash Street. However, the lower contact of the Palisade sill does not change elevation significantly over the same area. Therefore the contact between the sill and the country rock becomes stratigraphically lower to the south: the sill rests above a thick section of red clastics at Grandview (this Stop), but rests on the afore-mentioned tan sandstones at Piermont. This relationship could also be taken as evidence of onlap of younger strata to the north, but it might instead be due to a slight rise in the position of the Palisade sill, shifting the topographic high to the west.

According to Lawrence Blackbeer (pers. comm., 2001) tracks were recovered in these quarries by a quarry operator. They were sold to Blackbeer, and subsequently sold at Phillips auction house in New York City. ShayMaria Silvestri (Rutgers University) was kindly allowed to photograph these specimens; her photographs are reproduced here (Figure 27). The slabs reveal well-preserved unquestionable examples of large *Atreipus milfordensis* and *Brachychirotherium* cf. *B. eyermani*, the latter preserving skin impressions. The former are remarkably similar to specimens from the middle Passaic at Stop 6 of this field trip, also in the Blackbeer collection. *Atreipus* has also been described from an *in situ* occurrence in the Lower Lockatong Formation at Arcola, Pennsylvania (Olsen and Baird, 1986). The track-bearing layers have not as yet been identified at the present locality. As far as we know, these quarries have never been carefully prospected; additional searching could reveal important new material. *Because all of these sites are privately owned and residential, permission to prospect must be sought in every case, with due care given to private property and privacy.*

36.7 mi. Outcrop of tan arkose and gray and purple mudstone on right.

36.75 mi. Outcrops of tan arkose and gray mudstone and contact with Palisade sill are on northwest corner of Ash and Kinney streets. The red clastics seen in the Grandview quarries to the north are evidently at a higher stratigraphic level.

37.0 mi. Cross Sparkill Creek and turn right onto Ferdon Avenue. .Sparkill Creek flows through Sparkill Gap, which is where the ancestral Hudson River deviated from its present course and headed south west though the Palisade cuesta.

37.8 mi. Turn left onto Valentine Avenue.

37.9 mi. Turn left up dip slope of Palisade sill.continuing on Valentine Avenue to access Route 9W.

38.0 mi. Turn right onto 9W south floowing the strike ridge of the Palisade sill.

40.3 mi. Pass Lamont-Doherty Earth Observatory and New Jersey - New York state line.

43.7 mi. Turn left onto Alpine approach road.

43.8 mi. Continue straight ahead onto Henry Hudson Drive and Enter Palisade Interstate Park.

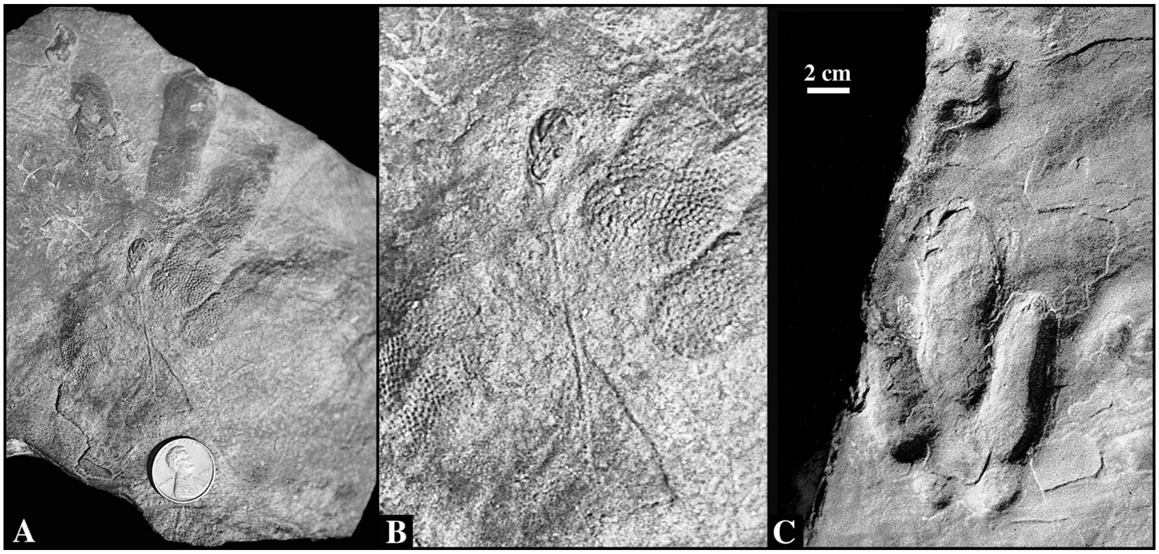

Figure 27. Footprints (all natural casts) from Grandview quarries: **A**, *Brachychirotherium* sp. with clear skin impressions; **B**, detail of skin impressions; **C**, *Atreipus milfordensis*. Specimens formerly in collection of Lawrence Blackbeer sold at auction.

Stop 3. Along-strike transect, Palisades Interstate Park, Alpine to Edgewater, New Jersey.

Latitude and Longitude: 40°56.393'N 073°55.285'W to 40°50.798'N 073°57.882'W

Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Lockatong and Stockton formations
Age: Late Carnian (Early Late Triassic); 225-226 Ma
Main Points:

1. Lateral transition from Stockton to Lockatong formations at basin edge
2. Marginal to deep-water lacustrine environments
3. Well-developed Van Houten cycles appear
4. Van Houten cycles very thin at hinge margin
5. Two cycles traced through basin with distinctive faunal patterns
6. Palisade sill as part of the CAMP event
7. Intrusion-related structures and sill contact
8. Distinctive facies of Stockton Formation with bones

Lockatong and Stockton sediments and their contacts with the Palisade sill are exposed at numerous places along the Palisade escarpment from Hoboken, New Jersey to Haverstraw, New, and permit a cycle-by-cycle correlation of the Lockatong for at least 15 km of this distance. The individual cycles were informally designated a series of letters and numbers (Olsen, 1980; Figure 28). Exposures in the Palisades Interstate Park, along Henry Hudson Drive and the Hudson River shore, from the Alpine boat basin to the park's entrance off of River Road in Edgewater, provide one of the best places to examine the lateral facies changes in the lower Lockatong and Stockton formations in northeastern New Jersey. In this along-strike transect we will have three mini-stops and five more significant stops (Figures 29, 30).

44.8 mi. Pull off on right side of road.

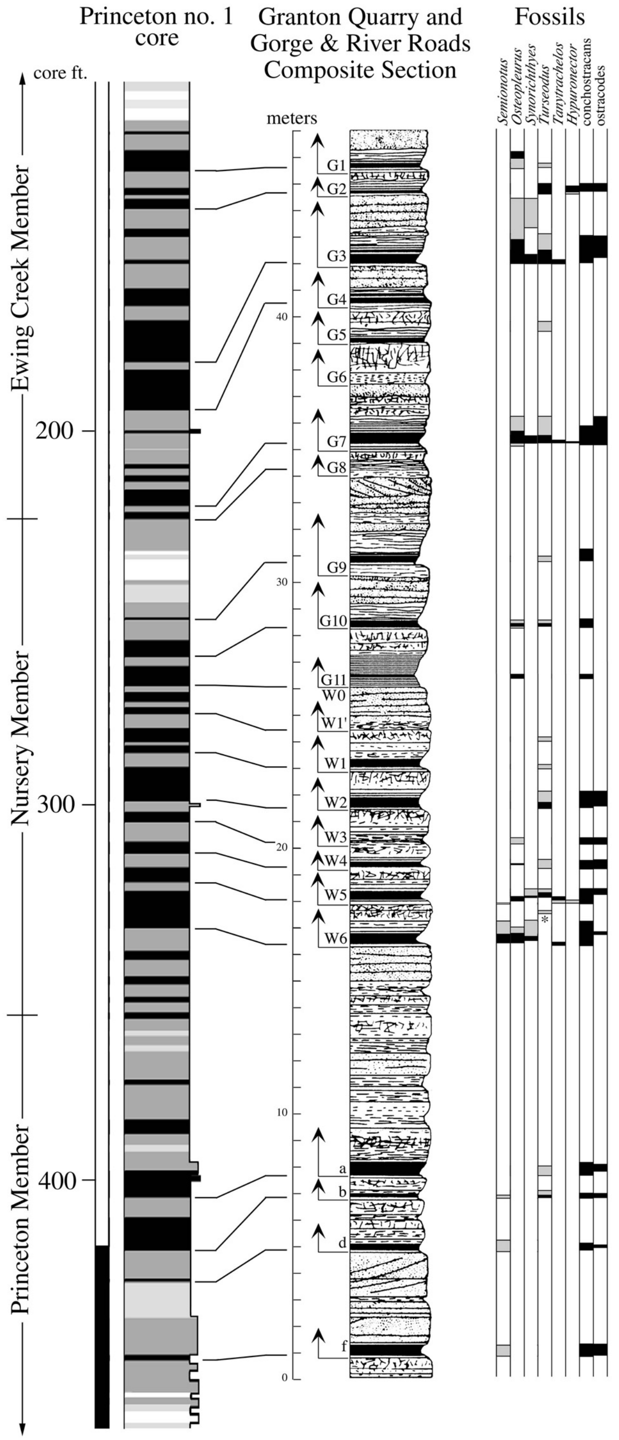

Figure 28. Composite section of Lockatong in vicinity of the Hudson River with the distribution of fossils and correlation to Newark basin coring project core, Princeton no. 1. Key for lithologies of the Princeton no. 1 core in Figure 4 and for northeast composite in Figure 34.

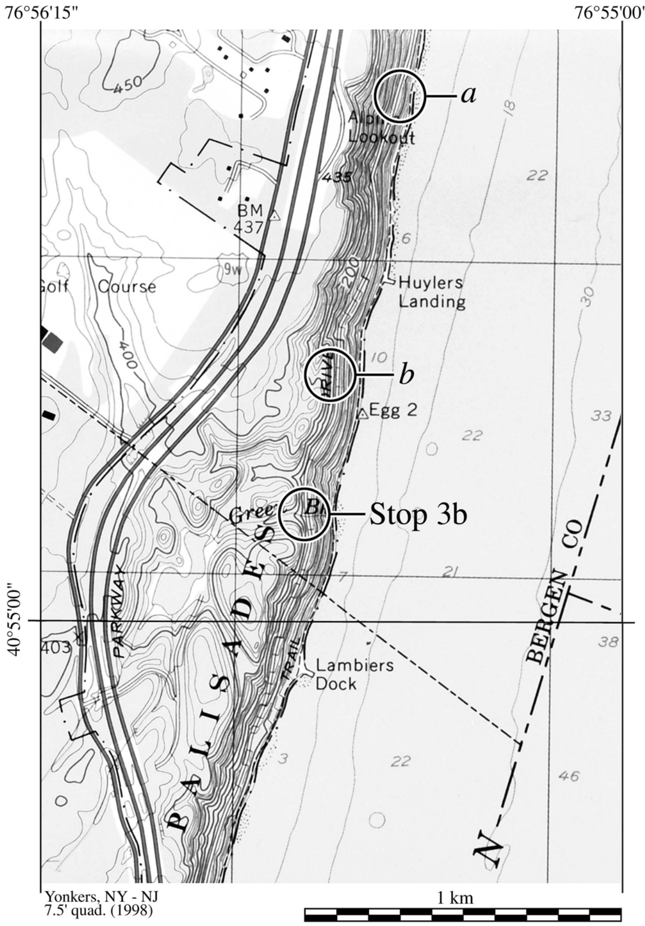

Figure 29. Location map for Stop 3a.

Ministop 3a: Stockton Formation entrance to Alpine Boat basin: **latitude 40°56.393'N, longitude 073°55.285'W.**

Tan and purple arkose with large-scale cross-bedding, and red and dark purple mudstone is exposed along the west side of Henry Hudson Drive and the traffic circle at the south end of the Alpine boat basin. Trough cross-bedding seems to dominate, with paleocurrents heading generally south and west. Given that this outcrop is near river level, it is more likely to be the lateral equivalent of those parts of the Stockton Formation fluvial sequence seen at Stop 3g (see below), rather than a lateral equivalent of the Lockatong Formation as seen at higher elevations (Stops 3b-3f). However, the strata also resemble the outcrop passed at Ash Street in Piermont (NY), which is probably the lateral equivalent to some of the Lockatong levels at Stop 3g.

To the north of the circle is the Alpine Boat Basin and the Blackledge-Kearny House. From the Blackledge-Kearny House (often reported as the headquarters of Cornwallis' assult on Washington's garrison), north there are excellent outcrops of the Stockton Formation very similar in facies to what is seen to the south, notably at Stop 3g. To our knowlege these have not been prospected for vertebrates, or studied.

Head south on Henry Hudson Drive.

45.4 mi. Cross bedding in Lockatong-Stockton lateral transitional facies along road; latitude 40°55.910'N, longitude 073°55.468'W. Currents heading south.

Another small outcrop of cross bedded tan arkose of the Lockatong-Stockton lateral transitional facies; latitude 40°55.432'N, longitude 073°55.607'W.

46.3 mi. Pull off on right side of road.

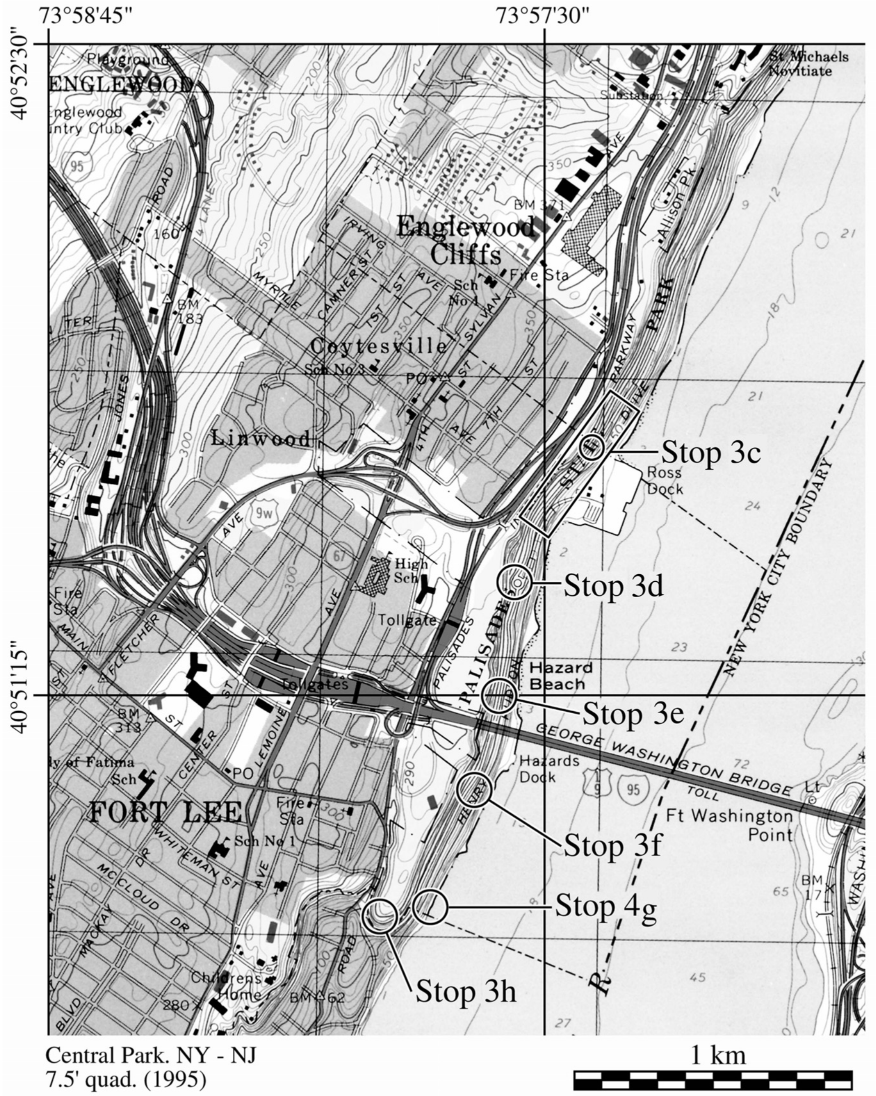

Figure 30. Location map for Stops 3b-h.

Stop 3b: Lockatong-Stockton lateral and vertical transitional, Greenbrook Falls, Alpine, New Jersey: **latitude 40°55.189'N, longitude 073°55.696'W.**

A shear cliff at the waterfall for Green Brook Creek and adjacent exposures on the west side of River Road reveal a long vertical section of the lower Lockatong and underlying Stockton formations. This is the only outcrop of this vertical transition known. Unfortunately, apart from the exposures along the road, the waterfall outcrops are virtually inaccessible and very dangerous. *Note that climbing is NOT permitted in the park.*

The roadside exposures show a small anticline in the still-cyclical lower Lockatong Formation (Figure 31). Here the cycles are considerably thicker than further south along the Hudson, and it is possible that these beds are part of a deltaic complex, changing laterally into the Stockton Formation. Here, each cycle averages about 4 m thick (N=2: Figure 32), consists of a gray massive to faintly parallel-bedded mudstone, overlain by crudely-bedded, locally cross-bedded and oscillatory-rippled tan arkose. These cycles do not show any hint of microlamination and vertebrate fossils have yet to be found. If the gray mudstones were slightly thinner and the irregularity of the bedding increased, this outcrop would be indistinguishable from some of the nearby units mapped as Stockton Formation. These units are probably the lateral equivalents of part of the Nursery or Princeton members at Stop 3c (below).

The anticline could be due to deformation caused by emplacement of the Palisade sill. More likely, it represents bedding distortion caused by modest gravity sliding along depositional relief at the lateral terminus of the Lockatong lake system.

Head south on Henry Hudson Drive.

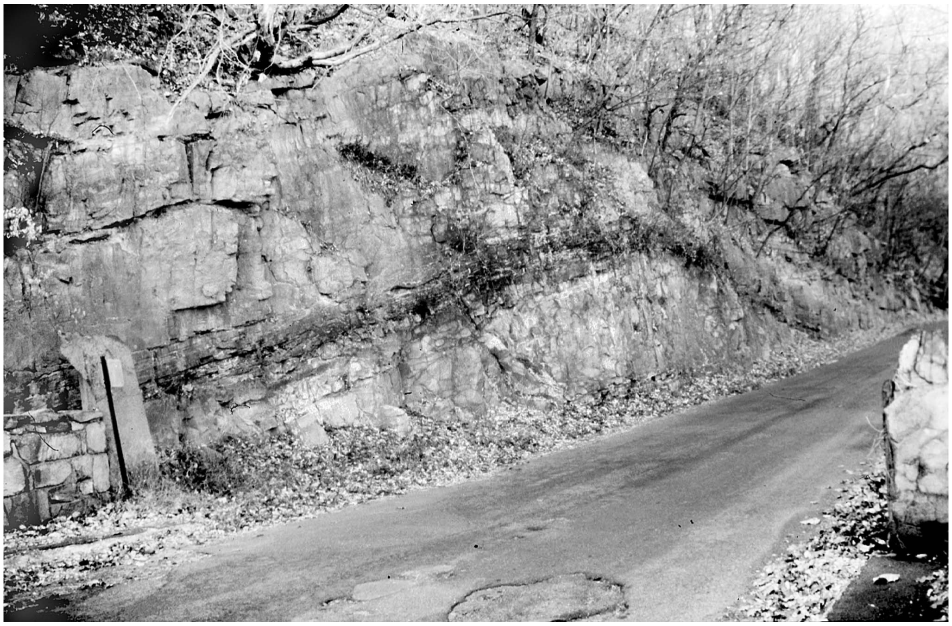

Figure 31. Anticline at Greenbrook Falls, Stop 3b. Prominent dark band is gray mudstone at 4 m in section in Figure 32.

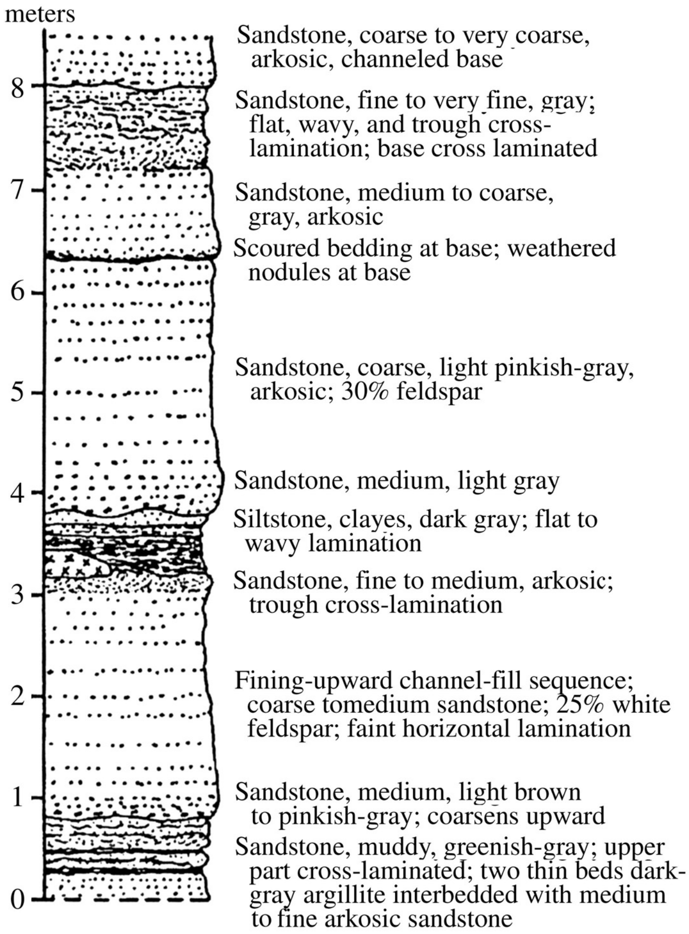

Figure 32. Measured section at Greenbrook Falls, Stop 3b (modified from Parker et al., 1988).

48.8 mi. Exposures of dark gray hornfels of laminated mudstone that appears to be part of cycle W6; 40°52.969, 073°56.705. At this outcrop the burrow *Scoyenia* penetrates the mudstone, consistent with a stronger surface modification and a nearshore environment.

50.6 mi. Pull off on right side of road.

Stop 3c: Van Houten cycles of lower Lockatong Formation, Henry Hudson Drive near Ross Dock: from 40°51.602'N, 073, 073°57.495'W to 40°51.777'N, 073°57.295'W.

These exposures comprise a long section though most of the Nursery and Princeton members at the northernmost outcrops at which these members can be unambiguously identified (Figures 29). This site has been previously described by Olsen (1980) and Olsen et al. (1989). We will begin at the north end of the exposure and proceed south, going up-section (Figure 33).

The series of Van Houten cycles in the Nursery and Princeton members of the Lockatong Formation are among the most distinctive in the entire Newark basin (Figure 34). Not only do they present a specific sequence of distinctive lithologies, but the faunal content of the cycles and the vertical changes in faunal composition is distinctive and persists laterally for at least 150 km (Figure 35). Two cycles in particular, - cycles W5 and W6 - are the lynchpin for the lateral correlation. These two cycles were quarried extensively at outcrops in Weehawken, New Jersey by a team from Yale University in 1979 and 1980 (Olsen, 1980) (Figure 36). More than 3000 specimens of fish and reptiles were recovered, resulting in a detailed sampling of faunal and taphonomic change through the two cycles (Figure 37, 38, 39). At Weehawken, the lower cycle (W6) has a very fine-grained clay-rich partially-microlaminated division 2. Articulated specimens of the tanystropheid *Tanytrachelos ahynis* are present in the transitional beds leading into the microlaminated portion of this division. However, most of the microlaminated portion of this cycle is dominated by the holostean fish *Semionotus braunii*, which was originally described by Gratacap (1886) and Newberry (1888) from a small exposure to the north of the Yale Weehawken excavations, although other fish are present - notably articulated specimens of the small coelacanth *Osteopleurus newarki*, which are relatively common in the upper part of the microlaminated interval. Division 3 is distinctive in that the lower part has a distinct interbed that marks a return to perennial lake conditions. This makes W6 appear as though it has a double division 2. This is characteristic of Van Houten cycles near the paleoequator, because there are two insolation maxima per 20 ky near the equator, rather than one, due to the twice-annual passage of the sun over the equator (Crowley et al., 1992; Olsen and Kent, 2000). Many Newark basin Van Houten cycles show hints of this pattern consistent with the basin's near-equatorial position, but none show it as strongly as cycle W6. Interestingly, this deeper water interbed has a different dominant fish - the palaeoniscoid *Turseodus* - represented, however only by disarticulated, albeit distinctive, elements.

The succeeding cycle, W5, has disarticulated rare *Semionotus* at its very base, associated with abundant disarticulated elements of the bizarre drepanosaurid diapsid *Hypuronector limnaios* (Colbert and Olsen, 2001) (Figures 8, 39), Above this, articulated *Osteopleurus* occur, but higher up, articulated *Turseodus* dominate the microlaminated interval. The microlaminated interval contains metamorphic minerals (e.g. diopside) that show that the laminite was much more calcareous than that of cycle W6. Virtually all of these features persist laterally from Weehawken northward to this stop (Figure 37).

Cycles W5 and W6 have also been identified in the NBCP cores and in outcrops in the southwestern part of the basin. Because of the distinctiveness of these two cycles, the correlation of the adjacent cycles is certain, and the pattern of cycles as well as their constituent fauna is maintained across much of the basin (Olsen at al., 1996a).

In contrast to sections further south that contain these cycles, this section contains the largest proportion of tan arkose, most notably in many of the shallow-water portions of the Van Houten and short modulating cycles. Much of this tan arkose exhibits oscillatory ripples, especially in division 1 of the cycles. Compared to sections further south, it is clear that the dry phases of the short modulating and McLaughlin cycles are abbreviated, with some parts even omitted (Figure 35). In addition, the degree of lamination is generally less. The average thickness of the Van Houten cycles at this stop

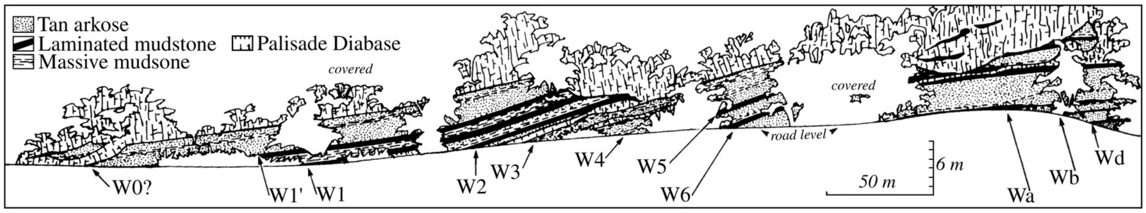

Figure 33. Panel diagram of the section along Henry Hudson Drive near Ross Dock (Stop 3c) showing the various cycles and the stratigraphically down stepping to the north of the Palisade sill (north is on the right). From Olsen 1980b.

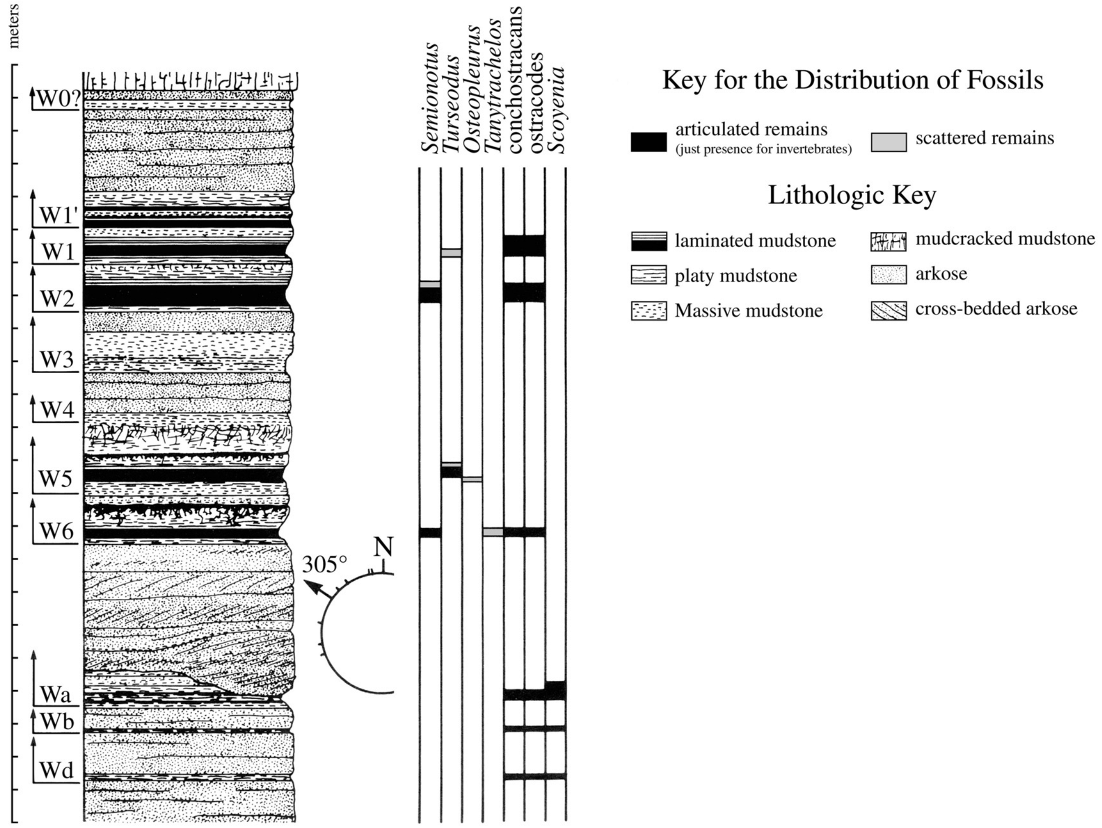

Figure 34. Composite stratigraphic section at Ross Dock with distribution of fossils. From Olsen (1980b).

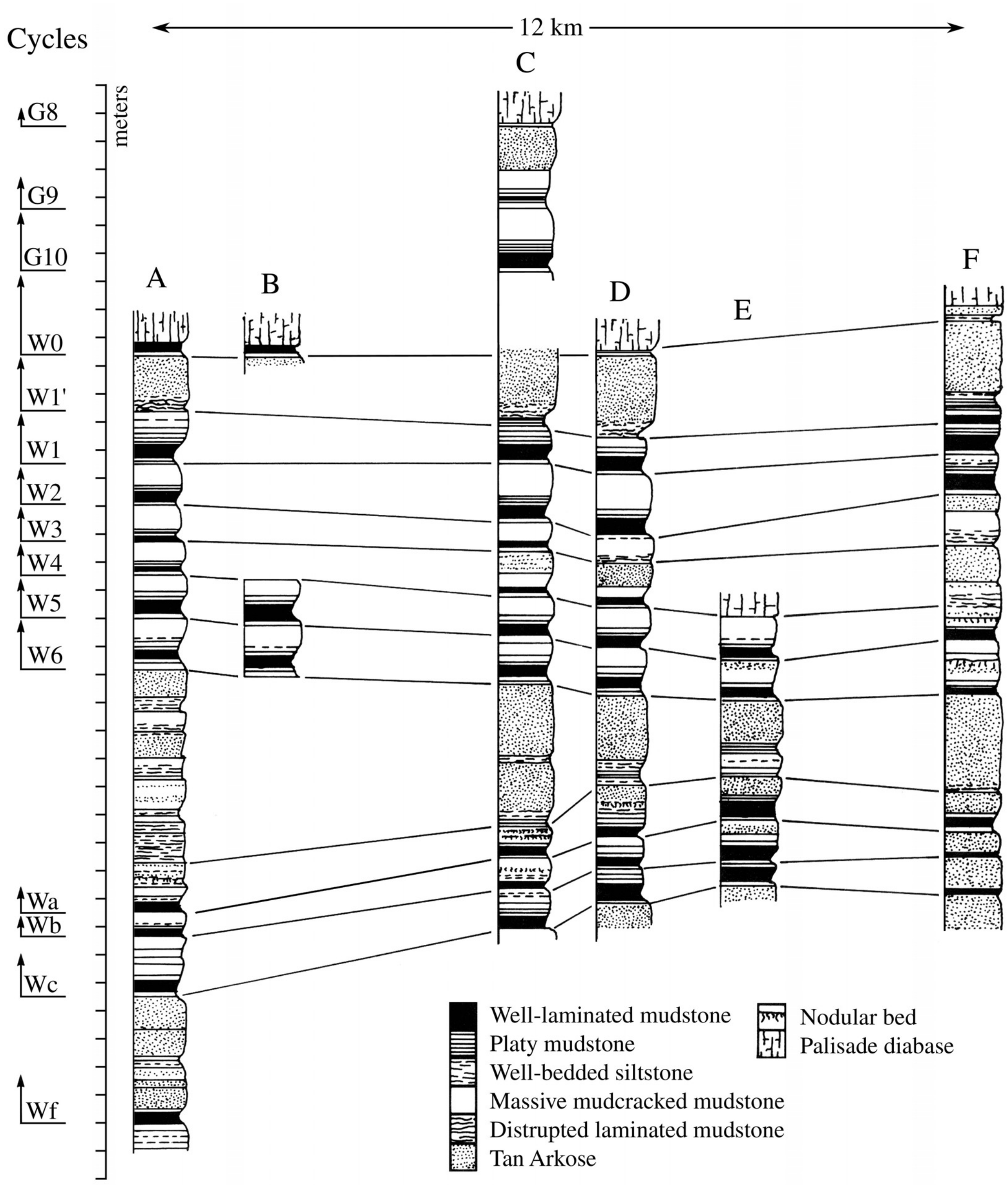

Figure 35. Lateral correlation of cycles from Kings Bluff (Yale quarry), Weehawken to Ross Dock area, Fort Lee (Stop 3c) (modified from Olsen 1980b): A, Kings Bluff exposure; B, Gratacap's (1886) Weehawken locality; C, George and River roads (Stop 4). Edgewater; D, east portal for old New York, Susquahanna Southwestern Railroad; E, "old trolley route" below former site of Palisades Amusement Park, Edgewater, New Jersey; F, Ross Dock area (Stop 3c), Fort Lee. Exposure A and F are 12 km apart; the other sections are positioned to scale.

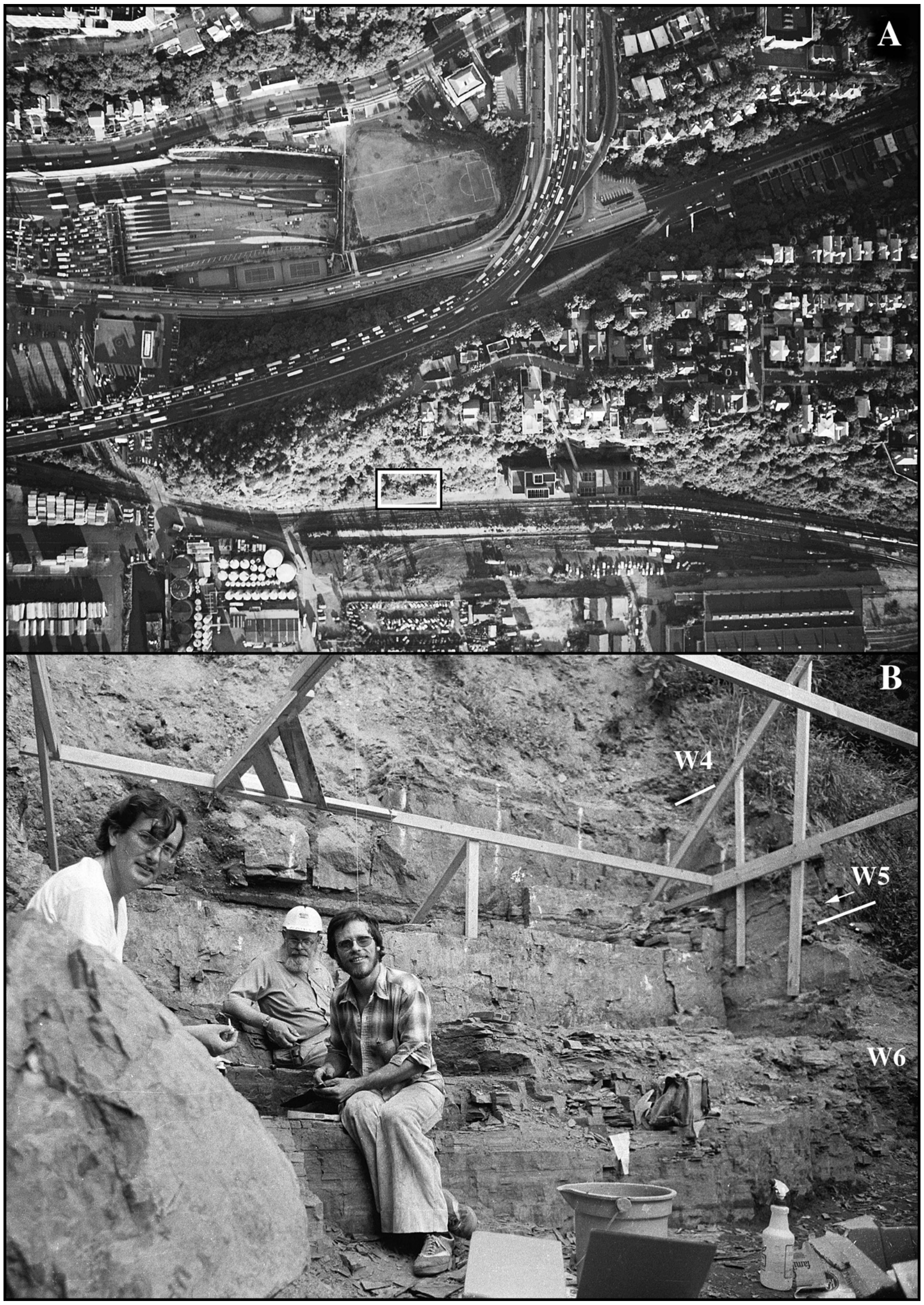

Figure 36. **A**, Aerial view of Weehawken Yale quarry location (box) at Kings Bluff, just south of the ventilation buildings for the Lincoln Tunnel (1979). Major highway is Interstate 495 feeding into the Lincoln Tunnel toll plaza (center, upper left). North is on right. Photo by William K. Sacco. **B**, Yale quarry, Weehawken, New Jersey showing the main cycles excavated at the site, 1979: from left to right, Keith Stewart Thomson, Donald Baird, Paul E. Olsen. Wooden frame was for identifying 3 dimensional position of all specimens recovered.

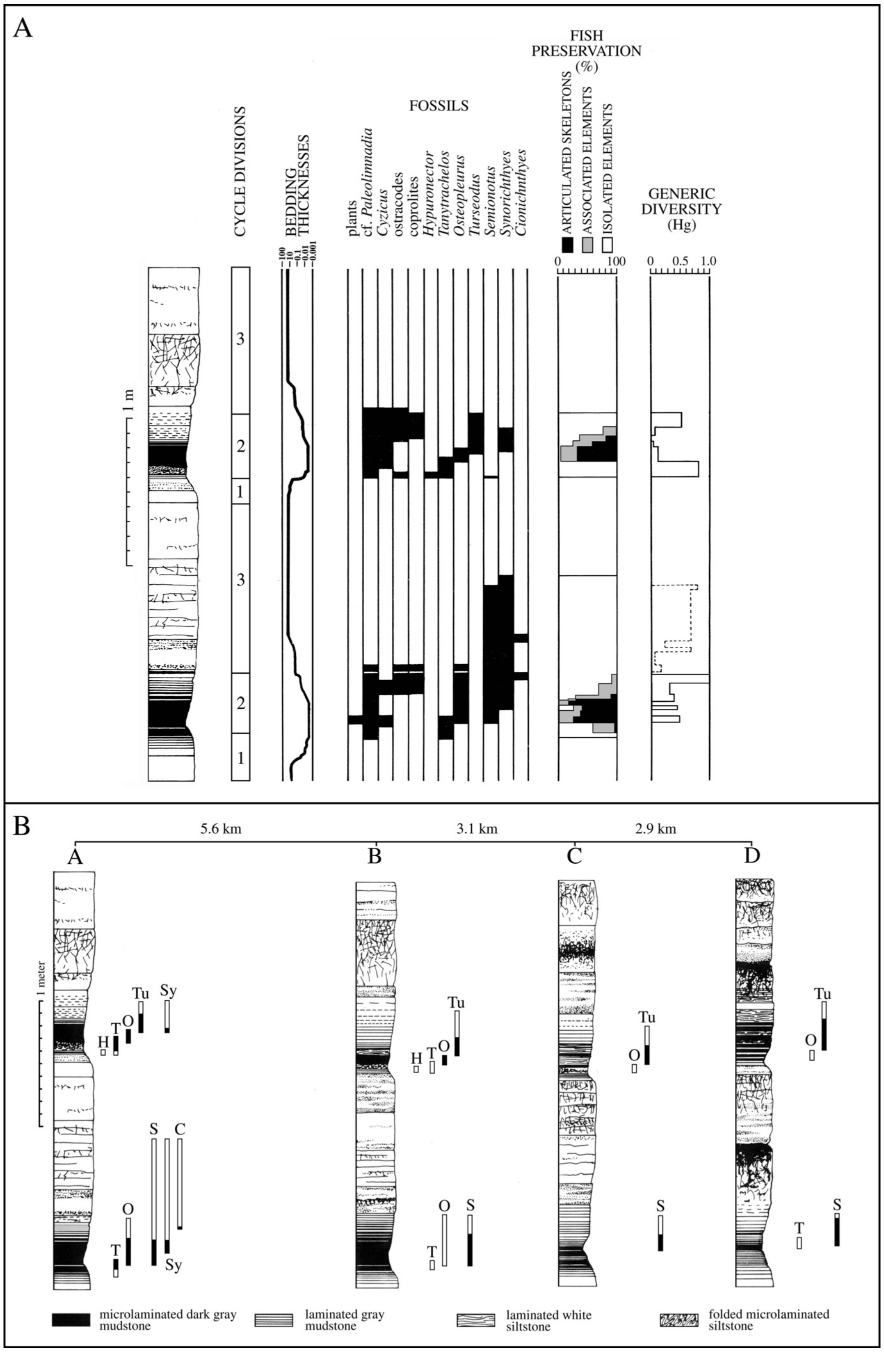

Figure 37. A, Microstratigraphy and biostratonomy of W5 and W6: key to lithologies as in Figure 34 except as shown. **A**, biostratonomy of W5 and W6 at the Yale quarry at Weehawken. Generic Diversity (Hg) is the Shannon-Weaver (1949) information index. **B**, Comparision of sections of cycles W5 and W6 along strike showing distribution and preservation style of fish: A, Yale Quarry, Kings Bluff, Weehawken; B, Gorge and River Roads, Edgewater (Stop 4); C, "Old Trolley Route", Edgewater; D, Ross Dock area (Stop 3c); C, *Cionichthyes*; H, *Hypuronector*; O, *Osteopleurus*; *Semionotus*; Sy, *Synorichthyes*; T, *Tanytrachelos*; Tu, *Turseodus*.

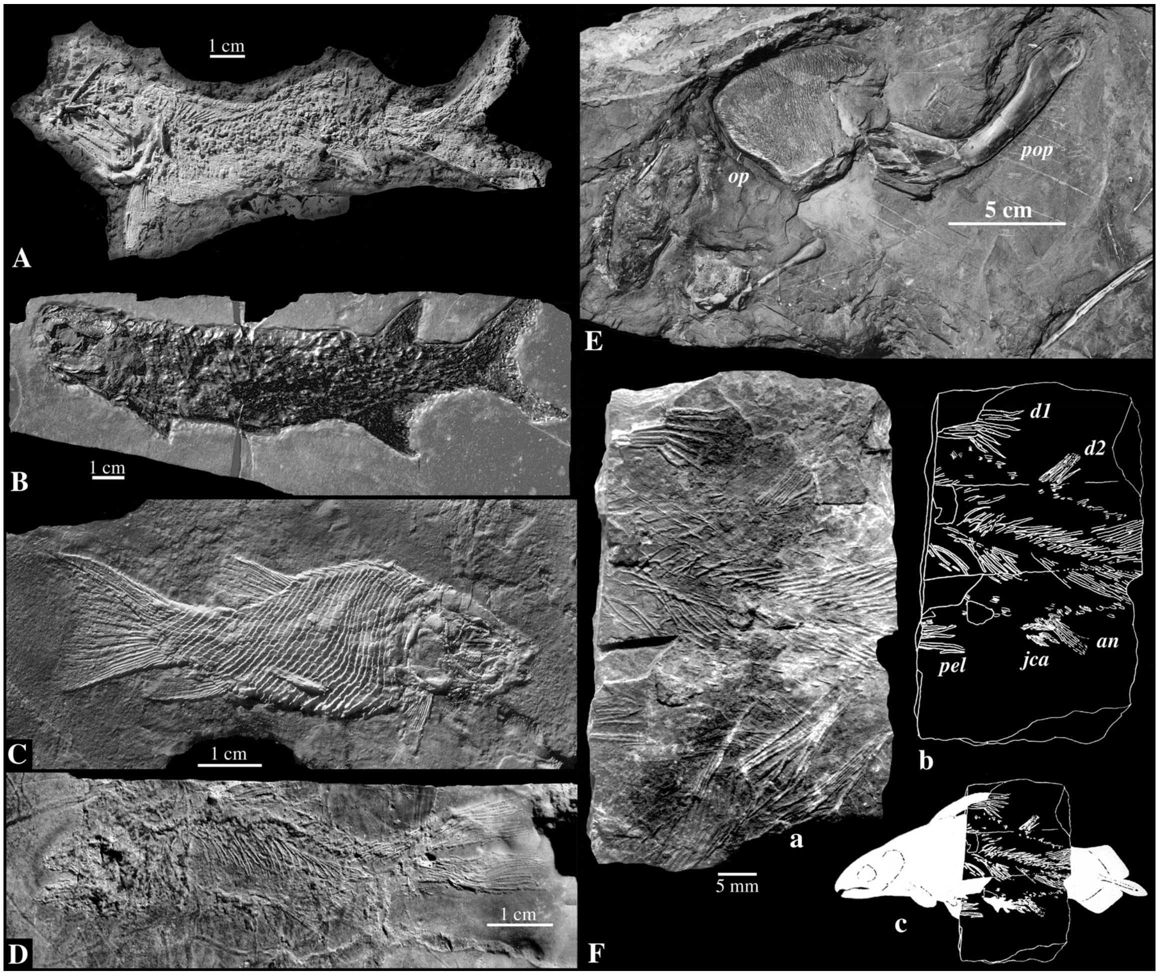

Figure 38. Examples of fish from Lockatong Formation. **A**, polysufide cast of the palaeoniscoid *Turseodus* sp. from cycle W-5, Yale Weehawken quarry (YPM field collection number W5-663). **B**, the refieldiid palaeonisciform *Synorichthyes* sp. from Gwynedd, Pennsylvania (YPM 8863). **C**, the holostean *Semionotus braunii*, from cycle W-6, W-5, Yale Weehawken quarry (YPM xxxx). **D**, the small coelacanth *Osteopleurus newarki* from cycle G-7, Granton Quarry (Stop 5). **E**, disarticulated partial skull of the large coelacanth cf. *Pariostegeus* sp. from float at Granton Quarry (Stop 5) (NJSM 16697: see Rizzo, 1999a): *pop*, preopercular; *op*, opercular. **F**, fragmentary, articulated specimen of *Osteopleurus newarki* from float at Granton Quarry (Stop 5) that seems to have been buried in the process of giving birth to a baby (see Rizzo, 1999b) (NJSM 15819): a, slab preserving mid section of probable adult and juvenile; b, drawing of same (*d*1, anterior dorsal fin; *d2*, posterior dorsal fin; *pcl*, pelvic fins; *an*, anal fin; *jca*, juvenile (caudal fin) in position of cloaca, just in front of anal fin); c, orientation of slab relative to outline of complete fish.

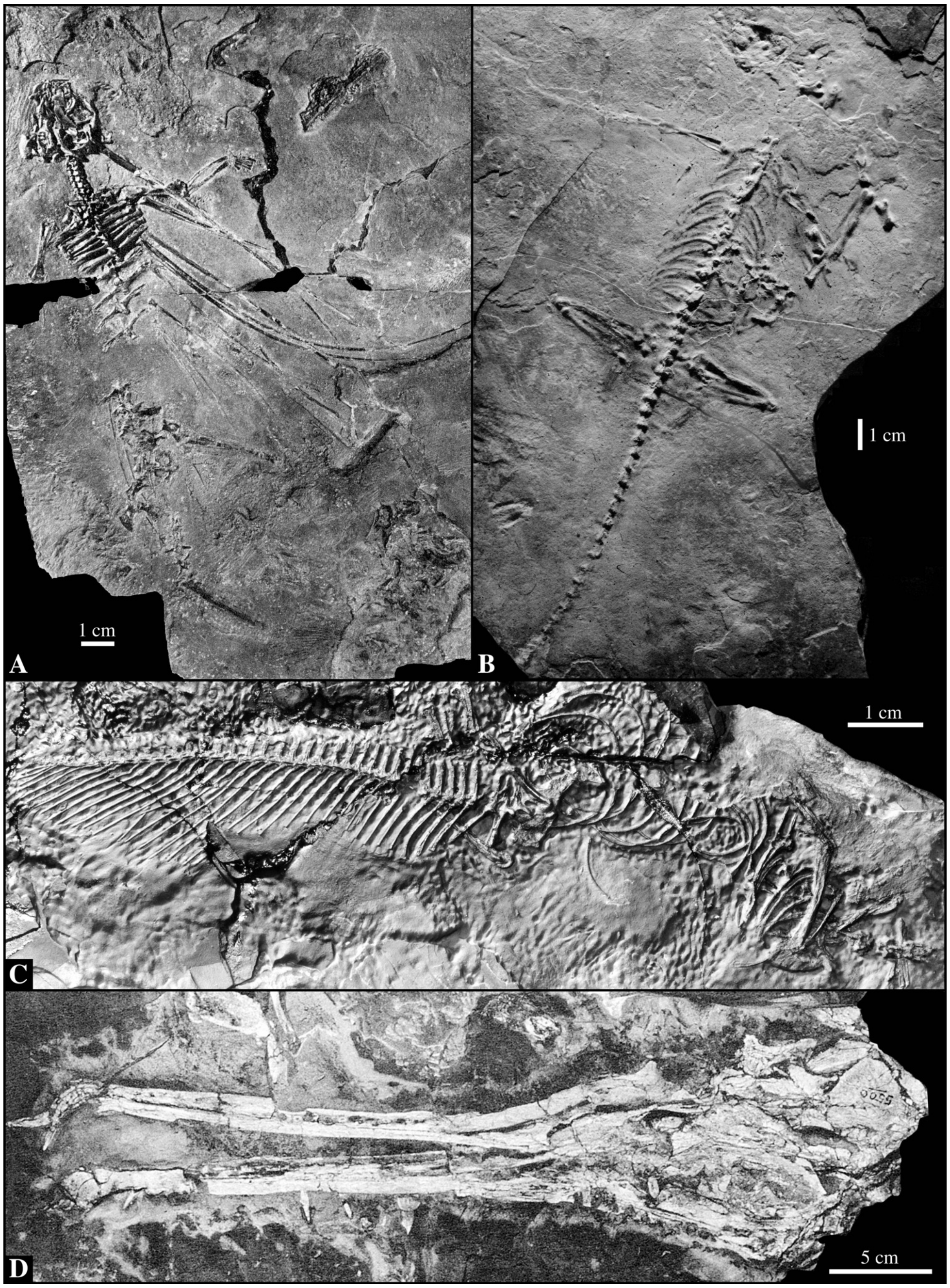

Figure 39. Reptiles from the Lockatong Formation at Granton Quarry (Stop 5): **A**, type specimen of *Icarosaurus seifkeri* from cycle G-3 (uncataloged AMNH specimen) (from Colbert, 1966; with permission of the American Museum of Natural History); **B**, female *Tanytrachelos ahynis* found by Steven Stelz, Trinny Stelz and James Leonard; **C**, type specimen of *Hypuronector limnaios* from cycle G7 (AMNH 7759) (from Colbert and Olsen, 2001; with permission of the American Museum of Natural History); D, skull of cf. *Rutiodon carolinensis* found in float (AMNH 5500) (from Colbert, 1965; with permission of the American Museum of Natural History).

is about 1.5 m. This is only about 25% of their thickness in the central Newark basin, and is consistent with the position of this section on the shoaling, hinge side of the basin.

On the whole, the distribution of vertebrate remains is consistent with stratigraphic equivalents further south, although the degree of articulation is less at this stop. In all cases at these exposures, bone and scale material is preserved as a translucent milky or pinkish phosphate, making it difficult to see. Combined with the extreme hardness of the metamorphosed sediment, this makes finding vertebrate material very difficult at this locality - although good specimens are present and can be found.

The underlying cycle, Wa is penetrated by numerous *Scoyenia* burrows (which were definitely not present at Stop 4) as are cycles Wb and Wc. We are clearly in the shallow-water facies of division 2 of cycles Wa-c at this point, but only just leaving the deep-water facies of division 2 in cycles W2, W5, and W6. Cycle Wa shows well-developed fracture cleavage in division 1. This cleavage dips 25° - 30° and strikes S78°W. It is strata-bound but discontinuous, passing laterally into breccia or non-cleaved beds. What is the significance of these structures?

The tongue of buff arkose between cycles W6 and Wa is thinner than at Stop 4 and displays unidirectional, oscillatory, and possibly hummocky cross-stratification, suggesting wave reworking of sheet deltas. Division 2 of cycle Wa is cut out by the arkose beds of this sequence by a channel-fill sandstone with mudcracked mudstone interbeds. Mean paleocurrent direction for these cross-beds is N59°W (based on 8 readings) (Figure 34).

In cycles W5 and W6 the degree of microlamination is significantly less than in these cycles further to the south, consistent with the rest of the section, significantly so in W5. The sequence of vertebrate taxa is still consistent with the pattern seen at Weehawken, but the degree of articulation has decreased. However, articulated *Tanytrachelos* and *Semionotus* are still present in division 2 of cycle W6. The upper part of division 1 of W6 has produced a partial arthropod, of uncertain relationships, about 20 cm long (Olsen, 1980). The most dramatic change from outcrops to the south, however, is that in this area, nodules, probably originally of carbonate, increase upward from the microlaminated portion of division 2 of cycle W6, coalescing into a nodular bed in the lower part of division 3, just below the more-laminated bed within division 3 that is such a distinctive feature of this cycle (Figures 34, 40). We interpret this nodular ?former-carbonate level as a caliche, developed in the dry lakebed of the lower parts of cycle W6. Hints of this caliche begin to appear in outcrops to the south (Figure 37).

Cycles 3 and 4 are evidently replaced by wave-influenced buff, cross-bedded arkose. Cycle 2 is very well exposed and contains the fish *Turseodus* and *Diplurus*. Cycle 1' is present, overlain by 4 m of arkose, but there is no sign of cycle 0, which presumably has pinched out or was cut out south of here. Cycle 1 is present but poorly exposed.

The facies trend in the Lockatong Formation from Stops 3 to 5 is from a basin-margin facies to a more central basin facies. The lateral heterogeneity seen toward the basin's hinge margin [Stops 3-5] gives way to monotony in horizontal continuity to the south. Those cycles with the best developed microlaminae and the best preserved fish at this stop are also those which persist the furthest laterally with the least change.

Figure 40. Exposures along Henry Hudson Drive, Stop 3c near Ross Dock showing cycles W5 and W6: *a*, nodular probable caliche horizon.

Continue south along Henry Hudson Drive.

50.8 mi. Pull off on right side of road.

Ministop 3d: Abandoned quarry in Palisade sill: latitude 40°51.460'N, longitude 73°57.534'W.

This old quarry, at the traffic circle at the ramp leading to Ross Dock, exposes the lower half of the Palisade sill (Figure 41). As noted by Walker (1969), the olivine zone of the sill produces an obvious bench along the escarpment to the immediate south, and elsewhere in the area, essentially paralleling the lower contact of the sill. In the cliff face, the olivine zone is marked by a zone of deflected columns. Flow banding is present within the olivine zone (Naslund, 1998).

Proceed south along Henry Hudson Drive.

50.9 mi. Pull off on right side of road.

Stop 3e: Concordant contact between Palisade sill and Lockatong Formation: latitude 40°51.253'N, longitude 073°57.587'W.

This comprises what is probably the most spectacular exposure anywhere in the basin of the Palisade sill with the underlying sedimentary rock (Figure 42). The contact is exposed for more than 50 m along strike, and reveals the intimate structure of the Lockatong-sill contact. The sill itself is part of a series of probably once-continuous sills and plutons that extended over almost the entire Newark basin, making this component of the CAMP one of the most extensive sills in the world.

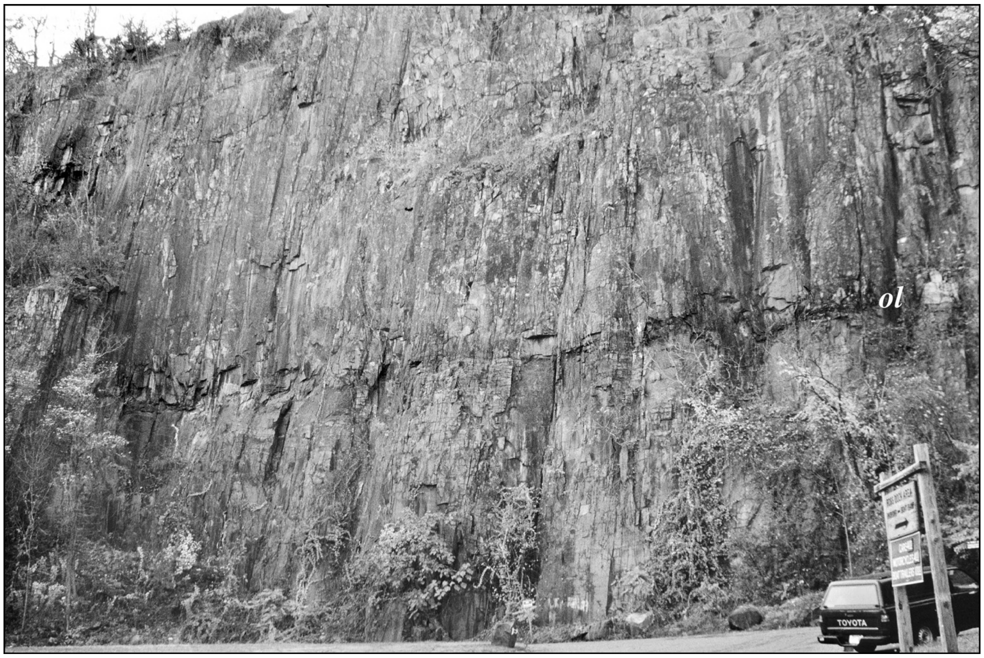

Figure 41. Quarry face at Stop 3d, with olivine zone (*ol*) in zone of deflected columns.

Figure 42. Mostly concordant contact of Palisade sill with mudstone and arkose of Lockatong Formation just north of the George Washington Bridge at Stop 3e.

Note that the contact is extremely sharp and that there is virtually no evidence of assimilation of sediment into the sill. Here and there the sediment-sill contact jumps a few tens of centimeters up or down, but on the whole it is remarkably concordant. Because so little thickness of Lockatong Formation is exposed here, we don't know what cycle is represented by this exposure.

Proceed south along Henry Hudson Drive.

51.2 mi. Pull off on right side of road.

Ministop 3f: Discordant contact between Palisade sill and Lockatong Formation: latitude 40°51.063N, longitude 073°5.672'W.

This exposure shows the contact between the Palisade sill and Lockatong Formation jumping first up several meters and then back down (Figure 43). The more mud-rich intervals appear to behave as if brittle, with essentially no assimilation into the sill, while the tan arkose appears to have flowed at the sill contact, with considerable chaotic mixing into the sill.

Proceed south along Henry Hudson Drive.

51.4 mi. At the middle of the sharp right turn to the west. cross over rock wall onto path, and walk down to the river's edge.

Stop 3g: Outcrops of Stockton Formation along Hudson River shore: 40°50.886'N, 073°57.727'W to 40°50.802, 073°812'W.

From just south of here to beneath the George Washington Bridge there are scattered outcrops of variegated strata of the Stockton Formation; their facies are characteristic of the units immediately below the Lockatong in this region. Tan, gray, and purple trough cross-bedded arkose and pebbly arkose grade upwards, through a series of irregular beds, into bright purplish-red massive mudstone, at meter-scale repetitions (Figure 44).

A partial disarticulated postcranial skeleton of a large phytosaur was recovered on private land just south of where the path comes down to the water's edge (Figure 44). It appears to have come from the transition between the arkose and red mudstone. The specimen was discovered in the summer of 1910 by Jesse E. Hyde, Daniel D. Condit, and Albert C. Boyle Jr., who were at the time graduate students of Prof. James F. Kemp of Columbia University. They contacted Barnum Brown and W. D. Mathew at the American Museum of Natural History (AMNH) in New York City, and the specimen was collected by Brown for the AMNH over a two week period in late December 1910, after a few months of negotiations with the land owners. (The phytosaur locality has been mis-identified in most published reports, and is usually cited as being "a half-mile south of the George Washington Bridge, opposite 155th St. [ref. and exact quote], even though 155th St is closer to 1 mile south of the bridge! However Mathew (1910) states that the specimen is from opposite <u>160th</u> St., which <u>is</u> approximately 1/2 mile south of the bridge; The specimen is also commonly referred to as the "Fort Lee phytosaur" (e.g. ref.),

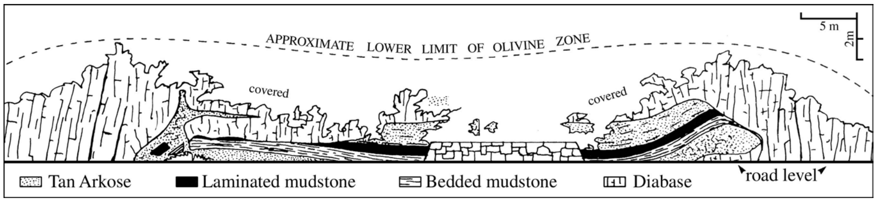

Figure 43. Sketch of discordant contact of Palisade sill and Lockatong Formation along Henry Hudson Drive just south of the George Washington Bridge at Stop 3f (from Olsen, 1980).

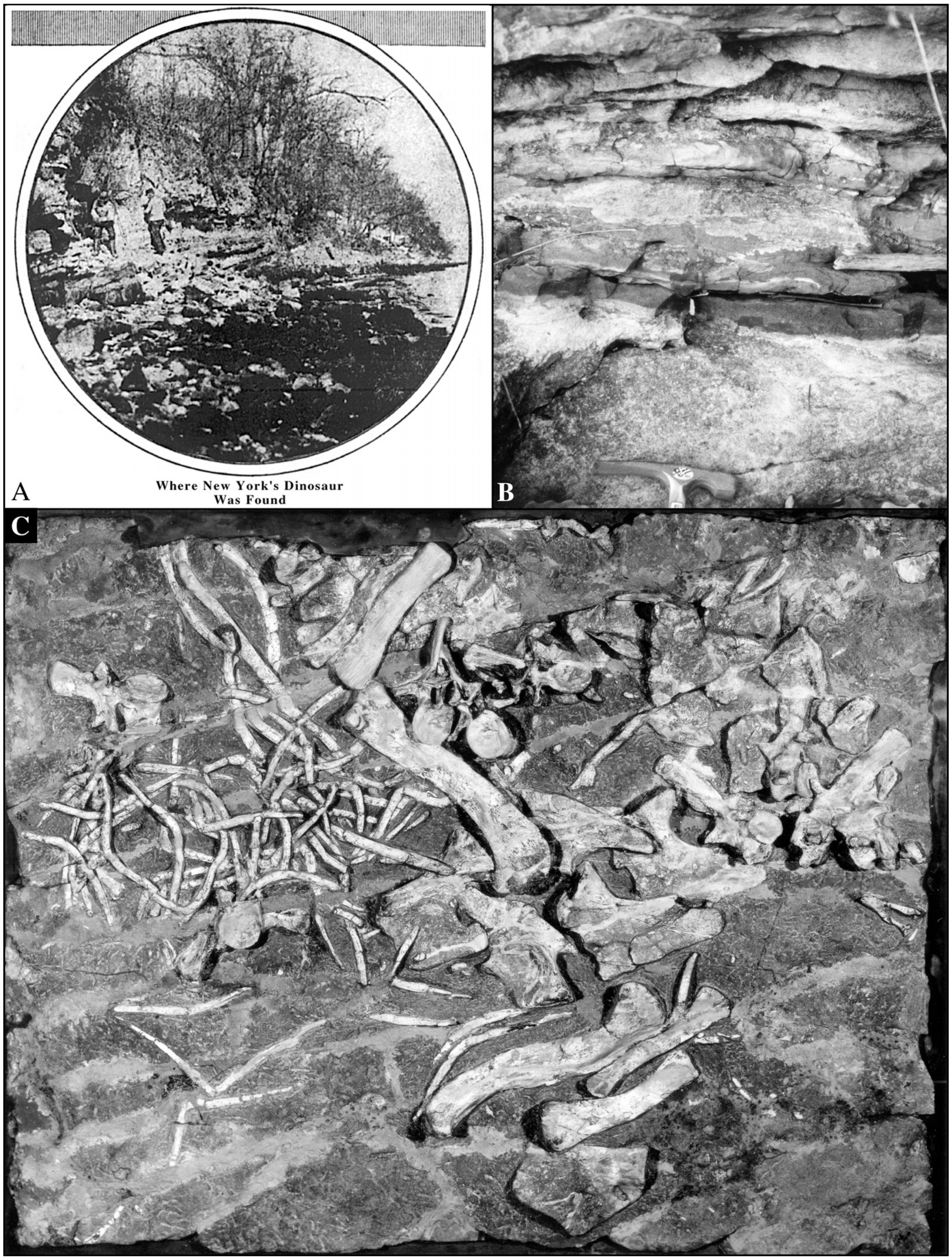

Figure 44. *Rutiodon manhattenesis* and outcrops at Stop 3g, Stockton Formation: **A**, photograph from the front page of the magazine section of the New York Times for December 25, 1910, showing the location of the phytosaur skeleton just south of the boundary with the Palisades Interstate Park (Stop 3g) (with permission of the New York Times); **B**, photograph of typical lithologies (purple and red mudstones and tan arkose) at the north end of the outcrops shown in A; **C**, disarticulated partial skeleton of the large phytosaur *Rutiodon manhattanensis* (AMNH 4991) (courtesy of the American Museum of Natural History).

although it is actually from Edgewater. The specimen (AMNH 4991; Figure 44) consists of several posterior dorsal, sacral, and anterior caudal vertebrae, both femora, tibiae, and fibulae, a few dorsal ribs, many gastralia, and numerous osteoderms. Huene (1913) described the specimen and named it *Rutiodon manhattanensis*. Based on the structure of the ilium, the generic assignment is correct (Huber and Lucas, 1993; Huber et al., 1993) but the specimen is indeterminate at the species level. This is the only vertebrate reported from this facies, but it suggests that further exploration should prove fruitful. AMNH 4991 is currently on exhibit in the Hall of Vertebrate Origins at the American Museum of Natural History in New York.

Walk back up hill to Henry Hudson Drive and proceed west toward intersection with Main Street (Fort Lee) entrance to the park.

51.6 mi. Stop at outcrops of diabase on north side of road.

Mini Stop 3h: Rotten olivine zone: **latitude 40°50.798'N, longitude 073°57.882'W.**

Here weathering profile of the olivine zone can be clearly seen. The olivine zone is weathered to a very crumbly diabase, that according to Naslund (1998) still has much fresh-looking olivine crystals.

51.8 mi. Leave park and turn left onto Main Street in Fort Lee and proceed south. Main Street becomes River Road once in Edgewater.

53.0 mi. Undercliff Road parallels escarpment on right. Stop 6.7 in Olsen et al. (1989) is along old trolley cut for Palisades Amusement park (Van Houten, 1969). Cut exposes upper Stockton and lower Lockatong Formation including cycles W5, W6, and Wa-c, as well as the contact with the Palisade sill including a large xenolith of cycle W5 within the sill.

54.4 mi. Turn right onto Old River Road.

54.5 mi. Exposures in old quarry in back of buildings exposing cycles W1-6.

54.6 mi. Driving over east portal of the tunnel for the former New York Susquehanna and Western Railroad. Cut below bridge comprises excellent exposures W1-6 and cycle Wa-c, (Olsen et al., 1989). Cycle W2 is very fossiliferous here with excellent articulated *Turseodus* and large disarticulated coelacanths (cf. *Pariostegus*).

55.2 mi. Park near truncation of Old River Road.

Stop 4. Gorge and River Road Section, Edgewater, New Jersey

Latitude and Longitude: 40° 48.458'N, 073° 59.534'W

Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Lockatong Formation
Age: Late Carnian (Early Late Triassic); 222 Ma
Main Points:

1. Long section of typical facies at hinge margin of Lockatong
2. Marginal to deep-water lacustrine environments
3. Well-developed Van Houten cycles in more basinward environment
4. Same cycles as at Stop 3c
5. Metamorphic mineral suite

A long section, recently expanded, is exposed along Gorge Road from its intersection with Old River Road to the contact with the Palisade sill at the Legend Hills Condominium development (Figures 45, 46). The same cycles seen at Stop 3c (from W6 upwards) are exposed here; however the section continues up into cycles not seen elsewhere along the east side of the Palisade sill, overlapping into the section exposed at Granton Quarry (Stop 5).

The most striking differences between this stop and the cycles seen at Stop 3c, are the increase in the degree of lamination in all cycles, and a decrease in the proportion of the cycles containing arkose. This is coupled with an increase in the abundance of fossils, especially fish and reptiles. The biostratonomy (*sensu* Schafer, 1972) of the cycles are now closely comparable to what is seen at the Yale Quarry at Weehawken, including such details as the presence of isolated bones of *Hypuronector* in the thin (~2 cm) massive gray mud at the base of division 2 of cycle W5. In addition the paleosol caliche in cycle W6 has disappeared and is replaced by massive mudstone.

We will begin at the north termination of Old River Road, on the south side of Gorge Road adjacent to 180 Old River Road. Cycles W5 and W6 and the underlying arkosic sequence are exposed near road level, but only W6 and the arkose are easily reached. The 5.5 m of arkose between cycles W6 and cycle Wa has some unidirectional cross-bedding indicating transport to the west and southwest (Van Houten, 1969), along with some wave-influenced sandstones, including some very handsome oscillatory ripples. (J.P. Smoot, pers. comm.). The arkose tongue and thin siltstones present in this interval are the lateral equivalents of relatively more shallow-water cycles present in the central Newark basin. Van Houten (1969) described the metamorphic minerals at this stop (Figure 45). Overall, from Stop 3c to this stop the facies trend, in terms of both lithology and fossils, is consistent with moving further away from the basin edge.

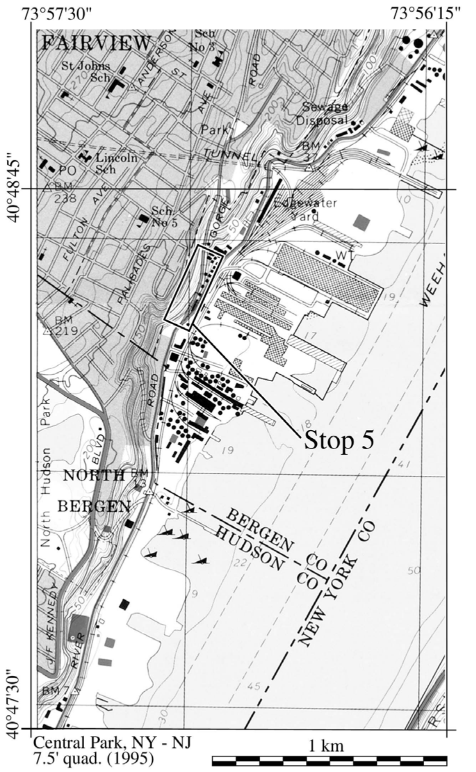

Figure 45. Map for Stop 4, Gorge and River Roads.

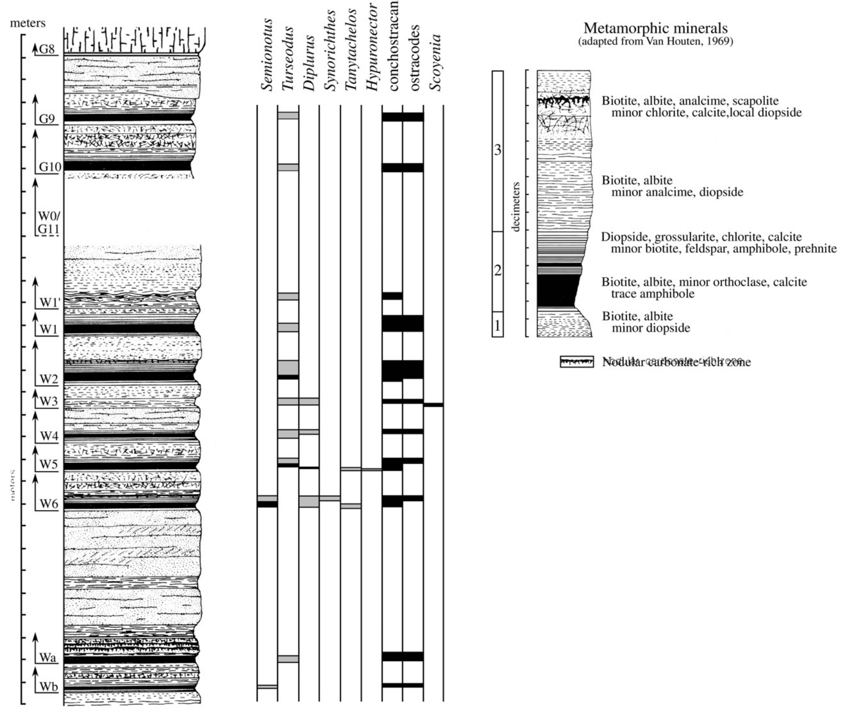

Figure 46. Section and fossils at Gorge and River Roads, Stop 4 (modified from Olsen, 1980b).

Proceed (with caution) east across Gorge Road, walk north along Gorge Road on the sidewalk, and then cross back to the exposures on the north side of the entrance road for the Legend Hills Condominiums. Lying in superposition on top of the sections exposed in 1980 are two more cycles separated by a gap of non exposure. The gap has to contain cycle W0 as seen at other nearby exposures. The two cycles are separated from the beautifully-exposed contact with the Palisade sill by a tan arkose sequence. Lithologically the two newly-exposed cycles resemble cycles W2 and W1, but are different enough that we can be sure they are indeed not simply structural repetitions of these cycles, but rather they are nearly identical to cycles G9 and G10 at Granton Quarry (Stop 5). Recognition of the identity of these two cycles at Granton Quarry is very important because it allows the sections on the east and west sides of the Palisade sill to be concatenated (Figure 28).

The arkosic sequence at the top of the section locally cuts deeply down into cycle G9; this is visible on both the south and east faces of the cut at the entrance to the Legend Hills Condominiums, and there is cross bedding visible within the the arkose. Just at the contact with the diabase, the arkose becomes very well-bedded and is capped by mudstone. This evidently marks the base of cycle G8 as seen at Granton Quarry.

Note that Gorge Road follows a fault-line ravine north of the Lockatong exposures; the eastern block is downthrown about 53 m (Van Houten, 1969).

Turn around, heading north on Old River Road.

55.2 mi. Turn right onto unnamed road.

55.25 mi. Turn right onto River Road.

55.28 mi. Turn right onto Gorge Road.

56.2 mi. Turn left onto Edgewater Road.

57.4 mi. Turn left onto Shaler Avenue.

57.5 mi. Cut in back of Shaler Avenue School is remnant of old quarry. Exposures consist of about 10 m of tan arkose and minor gray and purple mudstone of the upper Lockatong Formation.

58.0 mi. Turn left (south) onto Broadway (Routes 1 and 9).

58.7 mi. Cut for west portal of the tunnel for the former New York Susquehanna and Western Railroad exposes tan arkose (Parker, 1993).

59.3 mi. Turn right onto 83 Street.

59.5 mi. Turn left into back entrance for Tonnelle Plaza and drive up ramp to back of plaza complex.

59.8 mi. Park.

Stop 5. Granton Quarry, North Bergen, New Jersey.

Latitude and Longitude: 40° 48.431'N, 074 01.071'W
Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Lockatong Formation
Age: Late Carnian (Early Late Triassic); 222 Ma
Main Points:

1. The classic locality for Lockatong fossils
2. All reptile and fish taxa represented
3. Well-developed Van Houten cycles
4. Granton CAMP sill
5. Bedding plane faults as evidence of inversion

Remnants of the old Granton Quarry are preserved between the new Lowes Home Building Center on the south and Tonnelle Plaza (Hartz Mountain Industries) on the north (Figure 47). Granton Quarry was actively quarried for road metal, fill and rip rap during the 1950s and 1960s and was abandoned by 1970, whereafter it was slowly consumed by commercial developments and warehouses. Nonetheless, excellent exposures remain. The site has produced, and continues to produce, extraordinarily abundant fossils, especially vertebrates, and it is certainly one of the richest sites in North America for the Triassic (Figure 39). This is also the best locality on this trip to see the details of Lockatong-type Van Houten cycles. Eleven such cycles with a thin-bedded to laminated division 2 are exposed on the sill-capped hill: seven are exposed on the south-facing exposure (Figure 48), three additional cycles are exposed on the east-acing exposure; and all 11 cycles are exposed on the north-facing exposure, which is where we will examine them. The base of the section appears to be 38-46 m above the contact with the Palisade sill (Van Houten, 1969). This contact may be close to what was, prior to intrusion, the local Stockton-Lockatong formational contact. This section has been described in several papers including Van Houten (1969), Olsen (1980), Olsen et al. (1989), and Colbert and Olsen (2001).

According to Van Houten (1969), these Lockatong hornfels include calc-silicate varieties in the middle carbonate-rich part, and extensively feldspathized and recrystalized diopside-rich arkose in the upper part. Some beds of arkose show well-developed cross-bedding. Because of the buff arkose at the top of nearly every cycle, these are the most visually-graphic of the detrital cycles seen on this field trip; here the many correlated changes occurring though individual cycles can be easily seen (Figure 48).

Cycles G3 and G7 (Figure 48) have produced representatives of all the known skeletal remains of Lockatong vertebrates except the holostean *Semionotus*. The basal portions of division 2 of both of these cycles have extremely high densities of fossil fish, especially the coelacanth *Osteopleurus newarki* Schaeffer (1952). Small reptiles are also surprisingly abundant, and many important fish and unique reptile skeletons have been discovered here by dedicated amateurs and donated to various museums through the years (Colbert, 1965, 1966; Colbert and Olsen, 2001; Olsen et al., 1989; Schaeffer, 1952;

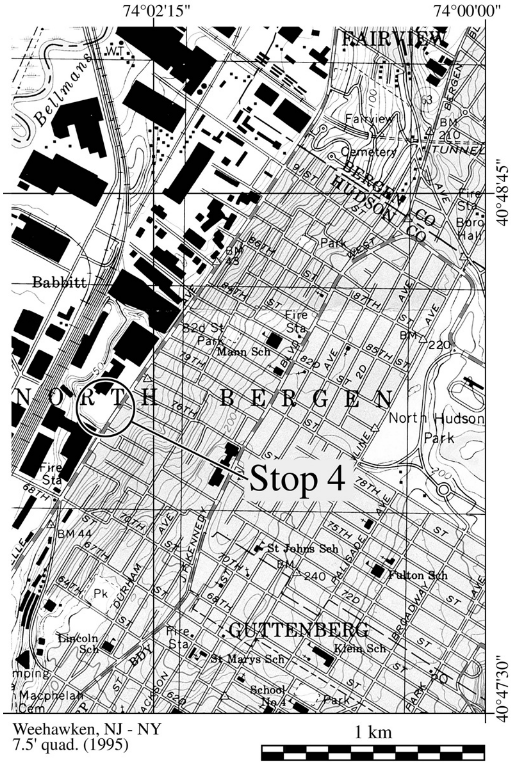

Figure 47. Map for Stop 5, Granton Quarry.

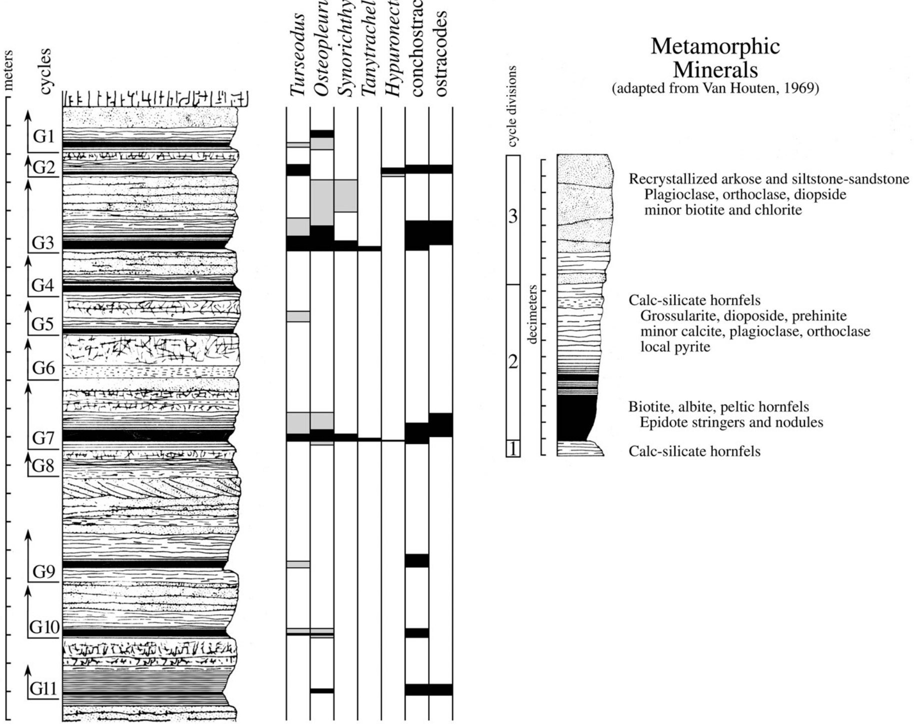

Figure 48. Section and fossils at Granton Quarry, Stop 5 (modified from Olsen, 1980b).

Schaeffer and Mangus, 1971). Without a doubt the three most spectacular skeletons of small reptiles found in the Lockatong come from the Granton Quarry. These include the type specimen of the bizarre "deep-tailed swimmer", *Hypuronector limnaios* (Colbert and Olsen, 2001), the peculiarly-abundant tanystropheid *Tanytrachelos ahynis* (Olsen, 1979), and the gliding lepidosauromorph *Icarosaurus seifkeri* (Colbert, 1966) (Figure 39). Larger remains occur as well, of which the most spectacular is the skull of a juvenile rutiodontine phytosaur (Figure 39), but isolated phytosaur bones and teeth are fairly common and isolated vertebrae of a metoposaur amphibian also been found.

Cycles G8 through G11 overlap with the section on the east side of the Palisade sill as exposed at Stop 4, as has been previously noted. A prediction of this correlation is that cycle W0 should be equivalent to G11. Examination of the eastern most outcrops at Granton Quarry of cycle G11 show that this is indeed the case. In fact this cycle is distinctive in having a very pyrite-rich division 2 that has strikingly bright yellow and orange clay seams on weathering, a feature not seen in other Granton Quarry cycles. With the sections from both sides of the Palisade sill combined, it is now possible to look at trends in lithology and biota at the scale of from a few thousand years (within one Van Houten cycle) to over 1 million years (i.e. three McLaughlin cycles) (Figure 28).

Although each cycle has its unique properties, there are prominent general paleontological patterns repeated in most cycles, which are well shown in cycles G7 and G3, that are common in Van Houten cycles in general (Olsen et al., 1989). The most obvious and least surprising pattern is seen in the correlation between the degree of fish preservation and the degree of lamination of the sediments. Microlaminated beds tend to preserve beautifully articulated fish, laminated mudstones produce disarticulated but still associated fish, and mudcracked mudstones have only dissociated scales and skull bones. This correlation almost certainly reflects the often-quoted dependence of fish preservation on a lack of oxygen, bioturbation, macro-scavenging, and physical disturbance.

Inversely correlated with this fish-preservation trend is one which at first appears very peculiar: a trend to <u>lower</u> fish diversity in the beds with the best fish preservation, and vice versa. This observation is based on the results from the Yale Quarry in Weehawken (Olsen et al., 1989) (Figure 37). This trend is all the more surprising because many more fish (individuals) are identifiable from the beds producing the best-preserved fish. The explanation seems to be that the highest diversity of lake environments tends to be near the shores, whereas the deeper-water zones tend toward low diversity (this is especially true for lakes with anoxic bottom waters, because they lack benthic forms). Thus, the cycle in fish diversity is a consequence of proximity to the shore which varies as a function of depth, which in turn controls the degree of lamination and absence of bioturbation.

The taphonomic pattern seen in the microlaminated division 2 of Van Houten cycles fits a chemically-stratified lake model (Bradley, 1929, 1963; Ludlam, 1969), in which bioturbation is perennially absent from the deeper parts of the lake bottom because the bottom waters lack oxygen, which is required by almost all macroscopic benthic organisms. Chemical stratification (meromixis) can arise by a number of mechanisms, but the main physical principle involved is the exclusion of turbulence from the lower reaches of a water column. This tremendously decreases the rate at which oxygen diffuses down from the surface waters, and retards the upward movement of other substances. The main source of water turbulence is wind-driven wave mixing. This turbulence usually extends down about one-half the wavelength of surface wind waves, which depends on the fetch of the lake, wind speed, and wind duration. If the lake is deeper than the depth of the turbulent zone, the lake becomes stratified with a lower non-turbulent zone and an upper, turbulently-mixed zone. The thickness of the upper mixed zone is also dependent on density differences between the upper waters (epilimnion) and lower waters (hypolimnion), which can be set up by salinity differences (saline meromixis) or by temperature differences, as seen in many temperate lakes. In the absence of saline or temperature stratification, chemical stratification can still arise in a deep lake with relatively high levels of organic productivity. Because oxygen is supplied slowly by diffusion, consumption by bacteria of abundant organic matter sinking into the hypolimnion plus oxidation of bacterial by-products eliminates oxygen from the hypolimnion. Lakes Tanganyika and Malawi in East Africa are excellent examples of very deep lakes in which there is very little temperature or density difference between the epilimnion and hypolimnion, but still chemical stratification occurs with the exclusion of oxygen below 200 m. Such a pattern is common in deep tropical lakes. The preservation of microlaminae and fossils in Van Houten cycles may have been a function of great water depth relative to a small surface area of the lake, which in the case of Lockatong lakes was none the less huge (in excess of 10,000 km^2); the depth, based on the area of the lake that must have been below the turbulent zone, was a minimum of 80 m during the deposition of the microlaminated beds (Olsen, 1990).

Thus, Van Houten cycles with a microlaminated division 2, such as G3 and G7 at Granton Quarry, and W5 and W6 at Stop 4, reflect the alternation of shallow, ephemeral lakes or subaerial flats with deep perennial lakes with an anoxic hypolimnion set up by turbulent stratification under conditions of relatively high primary productivity and low organic consumption (e.g. low ecosystem efficiency). The low organic content of divisions 1 and 3 of Van Houten cycles in general probably reflects higher ecosystem efficiency caused by shallow water depths, rather than lower total organic productivity.

This model also accounts for an exceptionally useful (for collecting) property of those cycles with a microlaminated division 2. Articulated small reptiles, such as *Tanytrachelos*, are found with predictable regularity in the basal few millimeters of the microlaminated unit. This pattern was first noticed in 1977 in Van Houten cycles in the upper member of the Cow Branch Formation of the Dan River basin (North Carolina and Virginia) (Olsen et al., 1978). The discovery of *Tanytrachelos* in the base of microlaminated units in this southern basin prompted a concerted search for reptiles in the homologous position in Van Houten cycles 500 km further north, in northeastern New Jersey. It took less than an hour for PEO to find the first skeleton, and that was at the locality described by Gratacap (1886) in Weehawken. Although Gratacap collected several hundred fish specimens from this site, no reptiles were found. That is, because without an appropriate model of why extra effort should be expended in those specific units, they get short shrift from the collector due to the presence of abundant fish in other parts of the unit. After the discovery of *Tanytrachelos* at Gratacap's locality, PEO informed Steven Steltz and James Leonard (two dedicated amateur collectors) about their predictable pattern of occurrence. The next time they visited Granton Quarry they found a complete *Tanytrachelos* (Figure 39) as well as pieces of other *Tanytrachelos* individuals, exactly where predicted. Prior to this, articulated *Tanytrachelos* had not been found at

Granton Quarry despite the fact the site had been a famous fossil locality for several decades.

With the sections on the east and west sides of the Palisade sill now combined, several larger-scale patterns emerge that are reinforced by data from elsewhere in the Newark basin. Looking at the distribution of fossil fish taxa through several cycles of different scales, a hierarchy of self-similar ecological patterns from the scale of the Van Houten cycle to the long modulating cycle is revealed. The full basic pattern of occurrence is, from oldest to youngest, *Semionotus*; *Semionotus* + *Osteopleurus*; *Osteopleurus* + redfieldiids (especially *Synorichthyes*); *Osteopleurus* + redfieldiids + *Turseodus*; *Turseodus* + redfieldiids, and finally just *Turseodus*. Most of this sequence can be seen in cycles W6 and W5 (Figure 37) at the Yale quarry in Weehawken, supplemented by data from the Eureka Quarry (Eureka, Pennsylvania). The pattern can also be seen within the short modulating cycle, e.g. N2 (which contains cycles W6 - W3). Thus, *Semionotus* is dominant in cycle W6, and *Osteopleurus* and *Turseodus* are dominant in cycles W5-W3. The basic pattern can be seen again in the McLaughlin cycle, such as the Nursery Member. *Semionotus* is abundant in short modulating cycle N2, near the bottom of the member, and *Osteopleurus* and *Turseodus* are dominant in short modulating cycles N3-N4. Finally, sequences of McLaughlin cycles, making up long modulating cycles, also show the pattern, with *Semionotus* being more common in the Princeton Member than in the Nursery Member, while *Semionotus* is virtually absent from the Ewing Creek Member. The distribution of fish taxa largely tracks the lithology of the fish-bearing units. More clastic units tend to be dominated by *Semionotus*, while more calcareous (or formerly calcareous) units tend to be dominated by *Turseodus*. In turn, the lithology is a function of paleoclimate, with more calcareous units being deposited higher in the cycles by more concentrated lake waters in drier times.

Interestingly, a very similar pattern is evident in Jurassic age strata of the Hartford basin (the Shuttle Meadow and East Berlin formations), Deerfield basin (the Turners Falls Formation, temporally equivalent to the East Berlin Formation), and probably also in the less well known Newark basin (Feltville, Towaco and Boonton formations). In these Jurassic age strata, *Osteopleurus* and *Turseodus* are absent, with *Redfieldius* being the only redfieldiid present. Again, *Semionotus* tends to occur low in the Van Houten, short modulating, and McLaughlin cycles.

The stratigraphic sequence in the Hackensack Meadowlands, underlying the Granton sill to the west of it's dip slope, consists of arkosic tan sandstones, overlain by black shales (that surely represent much of the remainder of the Lockatong Formation), which are in turn overlain by red mudstones of the Passaic Formation (Parker, 1993). If something like the average accumulation rate, based on the thickness of the Princeton, Nursery, and Ewing Creek members in the vicinity of North Bergen and Edgewater (i.e. 18 m/McLaughlin cycle), was maintained upward to the position of the Graters Member of the Passaic Formation (encountered in a boring; Lovegreen, 1974 cited in Parker, 1993), there is sufficient stratigraphic thickness in this area for the rest of the Lockatong and basal Passaic Formation.

At the south-facing exposures cycles G1 and G2 are injected by diabase of the 20 m thick Granton sill (Van Houten, 1969), another component of the CAMP, which has protected the Lockatong Formation from erosion in this area. Notice the absence of prominent folding at the diabase-sediment contact. Because this sill is thin, and the

Palisade sill fairly remote, much of the sedimentary rock is not as metamorphosed as at previous stops; some cycles still have considerable organic matter.

One or two bedding plane thrust faults, always thrusting to the east, are present in division 2 of nearly every cycle at Granton Quarry. Slickensides are usually present and indicate that movement occurred parallel to dip. All the joint sets are cut by these thrusts, their displacement indicating that each fault has a net slip of 0.5 to 1.5 cm. This type of minor thrust fault is evident in virtually all Newark Supergroup lacustrine cycles and can be seen at every stop of this trip. The fact that all of these faults are thrusts requires post-depositional northwest-southeast shortening, a steepening of dip, and a $\sigma 3$ that would have been vertical. This is completely incompatible with the extension that produced the basins; thus we take these faults as evidence for structural inversion.

Continue east.

59.9 mi. Turn right onto Routes 1 and 9 south.

60.5 mi. Dip slope of Palisade sill mantled by northwesterly dipping Lockatong Formation. Contact appears concordant from here to Granton Quarry.

60.8 mi. Contact of uppermost Stockton with Palisade Sill directly on left (east). Stockton dips 15 ° NW and the contact dips 45° to 80° NW. Recrystallized arkose of Stockton Formation is sheared and dragged upwards close to contact with slikensides indicating down-dropping to the west. There are no indications of movement in the diabase, however. Basal Lockatong hornfels 100 m to the north, dip 15° NW and lie concordantly on the Palisade Sill. A possible interpretation of these exposures might be that the apparent movement in the Stockton occurred during intrusion of the sill.

61.5 mi. On left is open cut in Stockton Formation and west portal of tunnel for Penn Central Railroad. Cut exposes upper Stockton beds described by Darton (1883) and Olsen (1980b). At east end of cut at tunnel is excellent exposure of the contact between the Stockton Formation and the Palisade Diabase. Stockton beds dip at 15° NW while the irregular contact dips at 60° NW. This contact is locally welded according to Darton (1890) and Lewis (1908). This appears to be a continuation of the contact surface exposed at the Penn Central tunnel described above and this is another exposure where the Palisade sill is described as having a dike-like appearance. Actually, these exposures and similar ones near by are perhaps better explained by a local stepping up of the Palisade sill as described by Olsen (1980b).

62.5 mi. Turn right onto entrance ramp for New Jersey Route 3 (and New Jersey Turnpike) and proceed straight ahead onto New Jersey Route 3 west..

64.3 mi. Ridge underlain by more resistant strata in proximity to the Graters Member. Outcrops of this member occur further south at abandoned diabase quarry at Laurel Hill.

64.9 mi.	Crossing over Hackensack River. At one stage or another the Hudson probably flowed along this route (Lovegreen, 1974).
66.9 mi.	Exit right for service road.
67.1 mi.	Turn right onto Orient Way: becomes Rutherford Avenue.
68.5 mi.	Turn left (south) onto Polito Avenue.
68.8 mi.	Turn right into parking lot for Ellen Tracy outlet store.

Stop 6. Bluff and Copper Prospect at Lyndhurst, New Jersey

Latitude and Longitude: 40°48.434'N, 074°06.506’W
Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Passaic Formation
Age: Late Norian (middle Late Triassic); 212 Ma
Main Points:

1. Part of ridge representing wet phase of long modulating cycle P4
2. Wetter facies better cemented
3. Kilmer Member of Passaic, marginal lacustrine facies
4. Vague pattern of Lockatong cycles
5. Accumulation rate similar to cored areas
6. Copper hosted in sandstones
7. Drier facies similar to more basinward facies with gypsum nodules
8. Footprints abundant in lake margin facies
9. Dinosaurs becoming larger and more abundant
10. Crurotarsans still very abundant

The Meadowlands are bordered on the west by a distinct ridge that extends from Hackensack to Kearny (NJ). For the most part this ridge is characterized by a heterogeneous assemblage of red mudstones and sandstones. However, there are a few purple and gray units present; based on their stratigraphic position they are part of long modulating cycle P4. The most eastern gray and purple unit probably is the lower part of the Kilmer Member (Figure 14).

Stop 6 is located on the eastern side of this ridge (Figure 49) and exposes the uppermost part of member T-U and the lower half of the Kilmer Member (Figure 50). In the central Newark basin, the basal Kilmer Member includes a prominent Van Houten cycle with a well-developed black division 2. In the region around New Brunswick (NJ), this black shale and the underlying division 1 of this cycle are often rich in copper minerals, so much so that during mapping of this member its surface trace became known as the “dead zone” because plants have trouble growing on the copper-rich regolith. There is surface evidence of copper prospect pits where and unnamed brook crosses the Kilmer Member in Piscataway (NJ), but these are not mentioned by either Lewis (1907) or Woodward (1944).

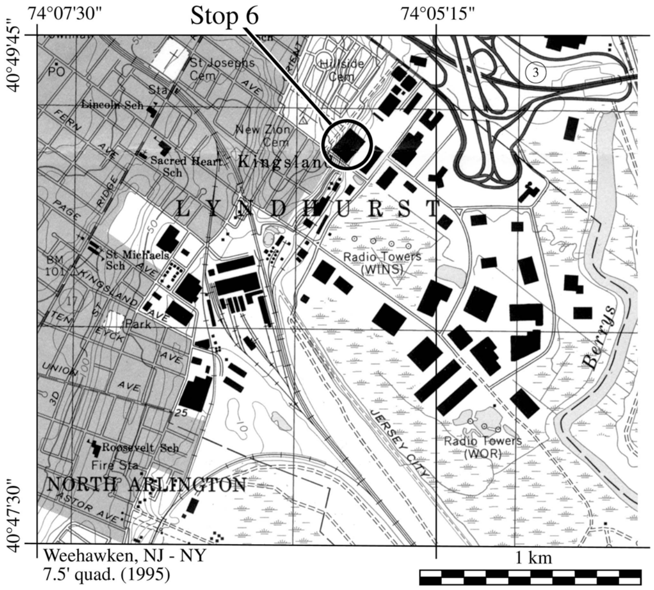

Figure 49. Map for Stop 6, Lyndhurst, New Jersey.

Figure 50. Exposures of copper-bearing white and tan sandstone surrounding purple siltstone of lower ?Kilmer Member at Stop 6, Lyndhurst, New Jersey.

In the outcrops in the northeastern Newark basin, the same Van Houten cycle apparently lacks black shale, instead having a purple shale with associated tan or white sandstones. The unit is still copper-mineralized, at least locally, and where intruded by thin diabase sills 2 km to the south-southeast in North Arlington (NJ), it was commercially exploited in what is supposed to be the oldest copper mine in North America – the Schuyler mine (Lewis, 1907). According to Woodward (1944), the Schuyler copper was discovered a few years prior to 1719 and an extensive mine was developed there, remaining profitable on and off until nearly 1830. In addition to copper it also produced a small amount of silver and trace amounts of gold. Possibly the first steam engine to arrive in North America (1753) was used to drain the mine, but the machine was damaged by fire in 1765, 1768, and 1773 (Woodward, 1944). There were several attempts at reopening the mine through the latter part of the 19th and earliest 20th centuries, but by 1903 the mine had been abandoned because of various engineering problems, and no doubt the much greater profitability of the copper deposits in the central and western United States.

The exposures at this stop may be the prospect mentioned by Woodward (1944) on the Kingsland estate, inspired by the Schuyler mine, but never worked extensively. An exploratory shaft at least was opened, and the now-cemented entrance is still visible. Tan and white sandstones associated with purple and gray mudstone are exposed, and mineralized with the same minerals as at the Schuyler mine, including chalcocite (black copper sulfide), chrysocolla (bluish-green copper silicate), malachite (green copper carbonate), and azurite (blue copper carbonate) (Figure 50).

The overall section at this stop consists of lower red massive mudstones of member T-U, followed by the tan and white sandstones surrounding a purple well-bedded mudstone of the basal part of the Kilmer Member. This is succeeded by massive red mudstones, a well bedded interval, and then red mudstones and fine sandstones with gypsum nodules. The overall stratigraphy is very similar to the expression of member T-U and the Kilmer member in the NBCP cores.

A large collection of very well-preserved reptile footprints was made near here by Lawrence Blackbeer in the late 1960s (pers. comm., 1985; Olsen and Baird, 1986). Although the exact location was not recorded, the lithology of the footprint slabs is consistent with the local expression of the Kilmer Member. The assemblage is distinguished in the Newark basin by the presence of relatively large grallatorid footprints, up to the size of *Anchisauripus tuberosus*; this is the oldest level in the basin with such tracks (Figure 51). The nomenclatural problems associated with these kinds of footprints are discussed in the text for Stop 7. Relatively large examples of the ornithischian dinosaur track, *Atreipus milfo*rdensis, are present, along with a new dinosaurian ichnogenus ("*Coelurosaurichnus*" sp. of Olsen and Flynn, 1989), as well as the non-dinosaurian *Brachychirotherium parvum*, and *Rhynchosauroides* sp.

Rhynchosauroides brunswickii and *Grallator* sp. were found specifically at this site by PEO during the early 1970s. PEO also found *Kouphichnium* sp., made by horseshoe crabs, as well as *Scoyenia* burrows. These trace fossils were all found in the red siltstones immeadiately above the gray sandstones.

Further southwest, (0.3) mi are additional exposures along former Erie Lackawanna Railroad tracks showing an unusual reverse fault dipping to the west and downthrown on the east. Slickensides confirm the dipslip nature of the fault.

About 2.9 km west of here on the west bank of the Passaic River are what were the Avondale and Belleville quarries that produced a large amount of building stone ("brownstone") to the region (based on location of quarries shown by Darton et al (1908). These quarries are now the location of Father Glotzbach and Monsignor Owens parks in Nutley (Avondale) New Jersey. These quarries produced a fragmentary phytosaur skull (Edwards, 1895; Lull, 1953; Baird, 1986b) as well as dinosaur footprints (Woodworth, 1895) and fragmentary plant remains (Nason, 1889). Unfortunately the whereabouts of the dinosaur tracks are unknown. The stratigraphic level of the quarries appears to be close to the Cedar Grove Member and almost certainly with in long modulating cycle P6.

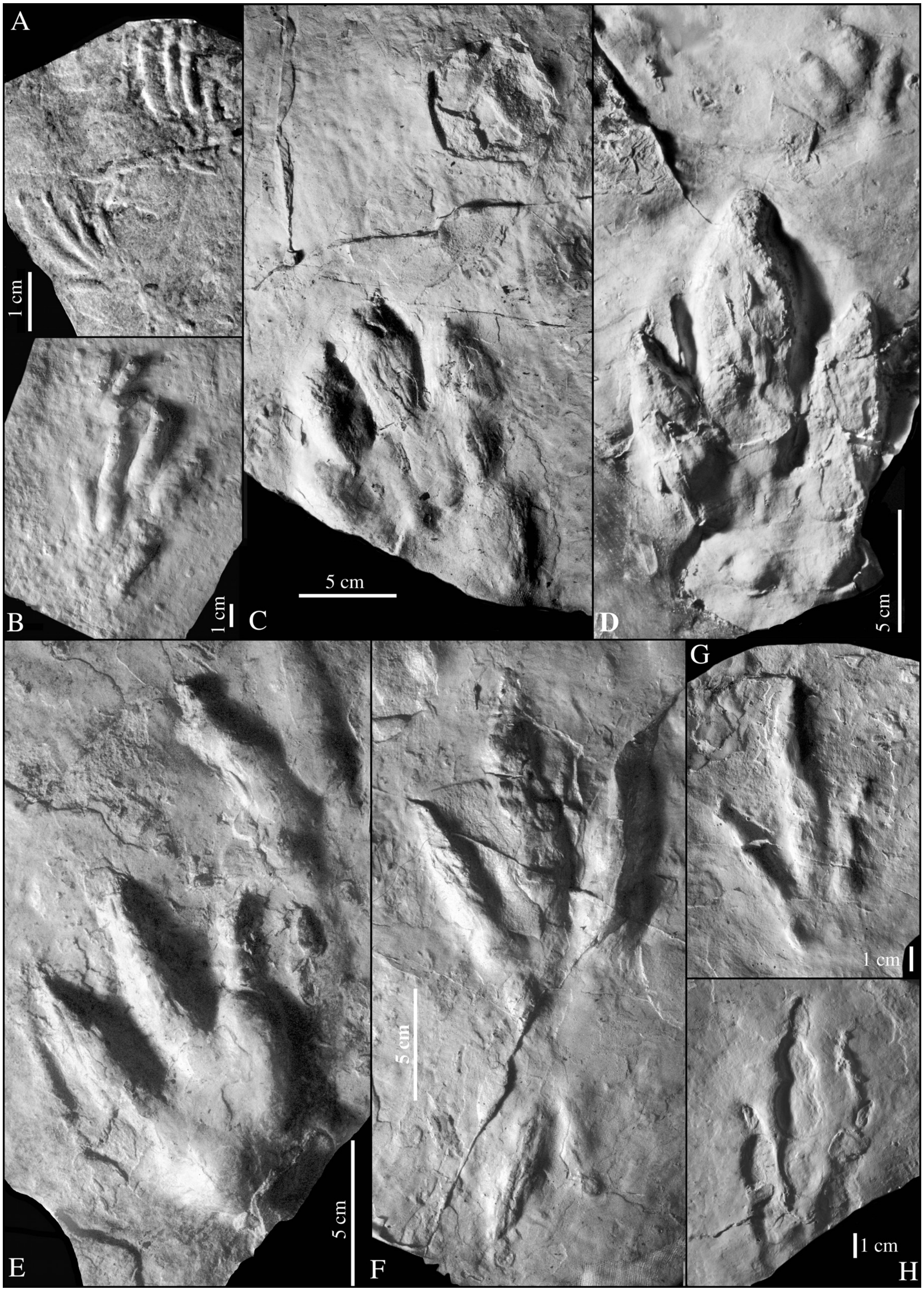

Figure 51. Footprints from Lyndhurst or vicinity, Lawrence Blackbeer collection (all polysulfide casts): **A**, lepidosauromorph track *Rhynchosauroides* sp; **B**, probable rauisuchian track *Brachychirotherium* sp.; **C**, probable rauisuchian track *Brachychirotherium parvum*; **D**, ornithischian dinosaurian track *Atreipus milfordensis*; **E**, ?saurischian dinosaurian track "new genus 1"; **F**, theropod dinosaur tracks *Anchisauripus* sp. (above) and *Grallator* sp. (below); **G**, theropod dinosaur track *Grallator* sp.; **H**, theropod dinosaur track *Grallator* cf. *G. parallelus*.

Return to Polito Avenue and turn left, heading north.

69.2 mi. Turn right onto Rutherford Avenue.

69.5 mi. Turn left onto ramp for Route 3 east (and New Jersey Turnpike).

69.9 mi. Enter onto Route 3.

70.6 mi. Exit for New Jersey Turnpike. Take New Jersey Turnpike (Western Spur) south.

75.4 mi. Exit 15W for Interstate Route 280. Take Route 280 west.

78.5 mi. Crossing Passaic River.

78.5 mi. Underpass for North 6th Street. Outcrop on right is a gray sandstone of the Cedar Grove Member. According to Neal K. Resch (quoted in Cornet (1977) The gray zone is roughly 4.8 m thick, the basal beds of which consists of 90 cm of black laminated shale passing upward into gray shale. This is followed by 60 cm of tan sandstone and 3 m of thinly bedded gray sandy shale and sandstone, grading upward into red sandstone. During the construction of Route 280, Resch collected conchostracans and leafy shoots of *Brachyphyllum* from the shale and various reptile footprints, including *Apatopus* sp.. *Brachychirotherium* sp., *Grallator* sp., and Anchisauripus sp. from the well bedded siltstone. Cornet (1977) described a palynoflorule from gray shale (sample SPPS-23A) indicating a probable early Rhaetian age. This unit was originally thought to be part of the Ukrainian Member, but Witte et al. (1991) show that the red beds directly overlying this gray sequence are of reversed polarity indicating correlation with the Cedar Grove Member.

80.6 mi. Exposures of Passaic Formation in cuts for connections to the Garden State Parkway.

83.4 mi. Exposures on left have produced a partial trackway of *Apatopus* sp., a phytosaurian trackway figured in Baird (1986b). This is amongst the youngest *Apatopus* know dating from about 500 ky before the Triassic-Jurassic boundary.

84.1 mi. Latitude 40°47.483'N, longitude 074°14.923'W. Huge cut in Orange Mountain Basalt - type section of the formation (Olsen 1980a) (modified from Olsen and Schlische in Olsen et al. (1989).

When this road was constructed in 1969, this 33 m high roadcut was the deepest federally financed highway cut east of the Mississippi River (Manspeizer, 1980). A complete section of the lower flow unit of the Orange Mountain Basalt is exposed (Figure 52) (Olsen, 1980a,c; Manspeizer, 1980; Olsen et al., 1989). Unusual curved patterns of columnar joints are present in the cut, described as chevrons, oblique and reverse fans, and rosettes. This flow overlies red beds of the Passaic Formation which contains the Triassic-Jurassic boundary 10 m or so below the basalt contact. During the construction of this cut in 1969, PEO found several examples of *Batrachopus* sp. just beneath the contact with the Orange Mountain basalt.

At this outcrop of the type section, the west-dipping lower flow of the Orange Mountain Basalt is almost completely exposed (Olsen, 1980a; Puffer, 1987). The Orange Mountain Basalt is an HTQ basalt (Puffer and Lechler, 1980) which at this exposure shows a complete, beautifully displayed Tomkeieff (1940) sequence (Olsen, 1980a; Puffer, 1987) almost exactly comparable to Long and Woods (1986); Type III flows. The thin (6 m) lower colonnade is fine-grained with large columns, the entablature is thick (35 m) with very well-developed curvicolumnar jointing, and the upper colonnade (10 m) is massive with poorly-developed columns.

According to Lyle (2000) the curvicolumnar jointing of the type seen at this outcrop are a direct result of ponded water on top of the cooling flows. The curved columns result from joints forming normal to large widely-spaced vertical master fractures in a hexagonal array that form very early in the cooling of the basalt flow. Water percolates down the mater fractures and provides a surface cooling faster than adjacent basalt resulting in surface-normal hexagonal fractures that propagate away from the master fractures and curving towards the upper cooling colonnade of the flow. The master fractures can be clearly seen separating bowl-shaped fans of the curvicolumnar jointing. Additional bowl-shaped fractures, as seen here may also have helped to control the radiating pattern of columns.

The largest fault in this exposure strikes N05°E, dips 80°E, and does not visibly offset subhorizontal cooling joints, suggesting that it is a predominantly strike-slip fault (Schlische, 1985). Another fault with a 25-cm-wide breccia and gouge zone strikes N30°E and dips 70°NW. Although slickensides suggest that the last slip on the fault was predominantly dip-slip, this fault may have originated as a normal fault during NW-SE extension. Several minor slickensided surfaces, mostly reactivated cooling joints in the basalt, show evidence of an earlier period of predominantly normal-slip and a later period of predominantly strike-slip (Schlische, 1985)

The Orange Mountain Basalt was probably fed by the Palisade sill (Ratcliffe, 1988) and it (and correlative units in other basins) represents the oldest of the known CAMP lava flows, flowing out less than 20 ky after the Triassic-Jurassic boundary (Olsen et al., 1996b).

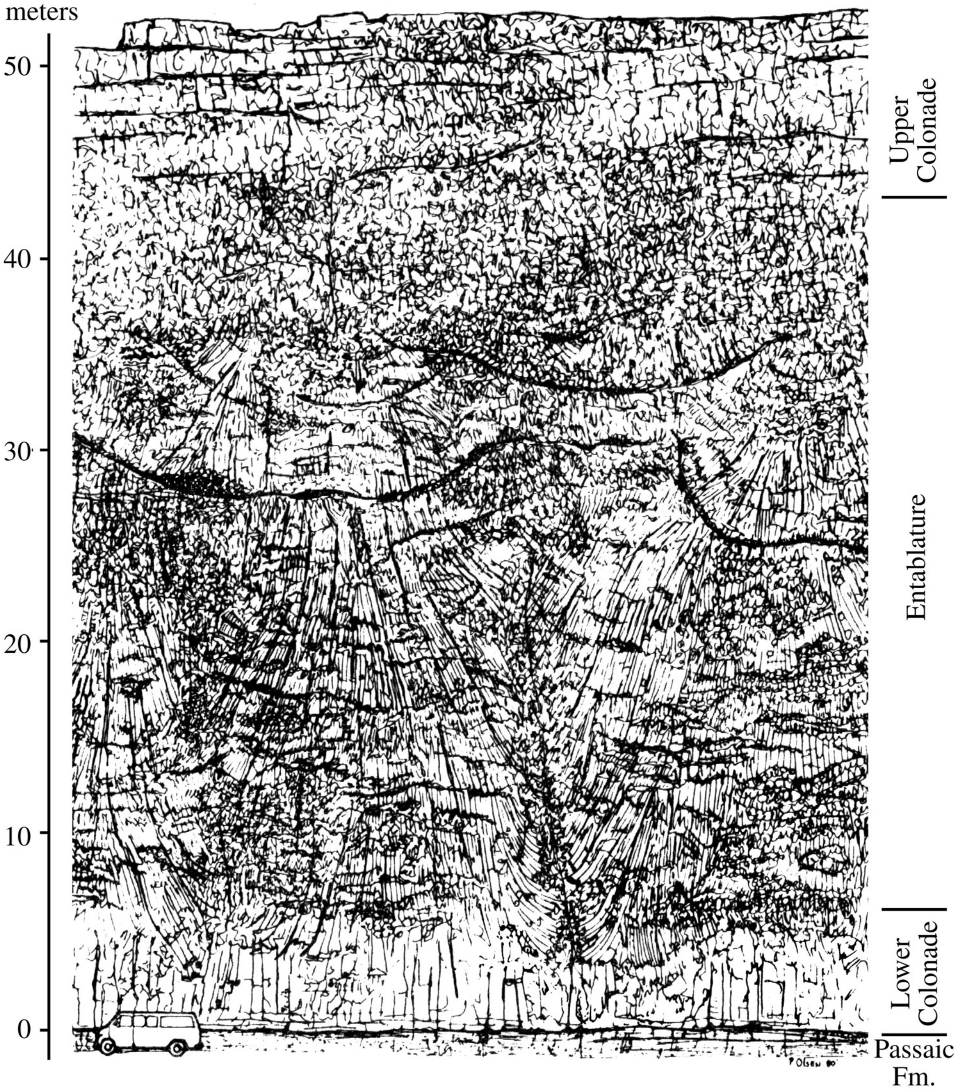

Figure 52. Composite drawing of the type section of the Orange Mountain Basalt along Interstate Route 280 in East Orange, New Jersey. Traced from a composite of a continuous series of photographs with the dip removed and compiled vertically (Olsen, 1980c).

84.9 mi. Exposures of ?second flow of Orange Mountain Basalt.

85.2 mi. Unexposed contact between Feltville Formation and underlying Orange Mountain Basalt below this point.

85.6 mi. Latitude 40°47.946'N, longitude 074°16.302'W. Contact between Preakness Basalt and Feltville Formation poorly exposed on south side of road and type section of the Preakness Basalt in deep open cut for Route 280 (modified from Olsen and Schlische in Olsen et al. (1989).

This type section (Olsen, 1980a.c) exposes about 100 m of the lowest flow of the Preakness Basalt, the thickest extrusive multiple flow unit in the Newark basin section (Figure 53). It is a high-Ti, high-Fe quartz-normative tholeiite indistinguishable from the Holyoke Basalt of the Hartford basin. The lowest flow is characterized by a thin lower colonnade; a massive, thick, and coarse-grained entablature with very characteristic splintery columns; a massive upper colonnade; and a comparatively thin vesicular flow top. It does not closely resemble any of the flow types of Long and Wood (1986), but it is similar to the second flow of the Sander Basalt of the Culpeper basin, the Holyoke Basalt of the Hartford basin, and some parts of the North Mountain Basalt of the Fundy basin.

The splintery columns are defined by what Faust (1977) calls a platy prismatic joint system, and it is characteristic of the lower flow throughout the areal extent of the Preakness Basalt. The joint system is not hexagonal and does not appear to be a faulting phenomena (although faulting does exaggerate it). Its origin remains a mystery.

Several faults cut the rocks at this exposure (Schlische, 1985) but most are now covered with gunnite for the safety of traffic. The largest fault zone strikes 005°, dips 85°E and is marked by a gully 1.5 m wide. The zone of brecciation varies in width from 40 to 60 cm. Slickenlines are curved from more steeply-plunging to more shallow-plunging attitudes. Another major fault strikes 035° and dips 83°NE and is marked by a breccia zone (with clasts 2 to 5 cm in size) 35 to 40 cm wide. Slickenlines rake 35°N. Three other macroscopic faults have orientations 010°, 82°NE; 040°W, 82°NE; and 020°, 83°NE; brecciated zones are 10 to 15 cm wide. A systematic study of minor fault populations showed that, although most of the faults followed pre-existing joints within the basalt, the slickenside striae strongly indicated strike-slip on NW-striking planes (Schlische, 1985), consistent with the larger faults at this exposure.

At this locality the contact (now overgrown) with the underlying Feltville Formation is simple, with massive basalt of the lower colonnade in direct contact with sedimentary rocks. At other localities thin flow units, pillow lavas or rubble flows are present (Olsen, 1980a).

89.0 mi. Take exit 4A onto Eisenhower Parkway south paralleling to the south the ancient course of the Hudson. Entering former course of Hudson River (Johnson, 1931).

89.6 mi. Intersection with Eagle Rock Avenue.

89.9 mi. Intersection with Nob Hill Road. Outcrop on left is of the two flows of the Hook Mountain Basalt and underlying upper Towaco Formation described in Olsen et al. (1989, Stop 6.3).

90.1 mi. Turn left onto Beaufort Avenue.

90.5 mi. Turn left onto access road for the Essex County Art Park and drive up the dip slope of the Hook Mountain Basalt..

91.0 Park in uppermost lot of Essex County Art Park. Follow path down to Walter Kidde Dinosaur Park.

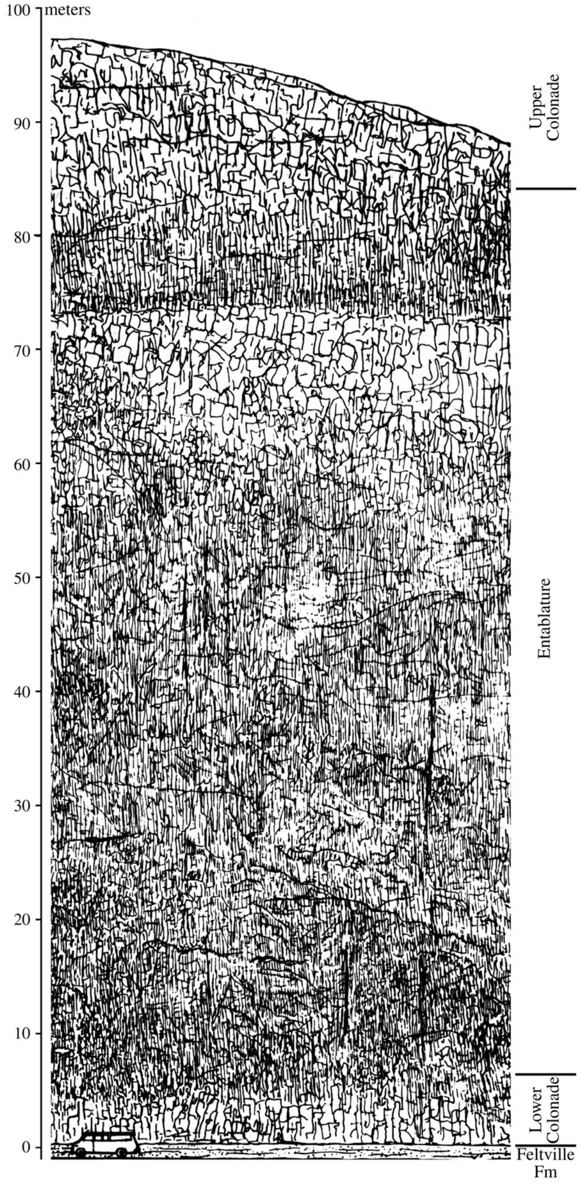

Figure 53. Composite drawing of the type section of the Preakness Basalt along Interstate Route 280 about 2.25 km west of the type section of the Orange Mountain basalt (Figure 52). Traced from a composite of a continuous series of photographs with the dip removed and compiled vertically (Olsen, 1980c).

Stop 7. Walter Kidde Dinosaur Park, Riker Hill, Roseland (New Jersey)

Latitude and Longitude: 40°48.920'N, -074°19.550'W
Tectonostratigraphic Sequence: TS IV
Stratigraphic Unit: Towaco Formation and Hook Mountain Basalt
Age: middle Hettangian (Early Jurassic); ~202 Ma
Main Points:

1. Long section of upper Towaco Formation: type section
2. Very thick Van Houten cycles
3. Peak wet phase of long modulating cycle H1 and Laskar cycle LaCV1.
4. But dry phase of 404 ky cycle
5. Footprints very common in lake margin sheet deltas
6. Typical earliest Jurassic assemblage
8. Extraordinary preservation
7. Includes level of Dinosaur State Park in Hartford basin
8. Level of unique assemblage of track types, including synapsids
9. Association with waning phases of the CAMP

The discovery of dinosaur footprints in the "Riker Hill" (aka "Roseland") quarry - part of which is now the Walter Kidde Dinosaur Park (Figure 54), was first reported in the local newspapers of Livingston and Roseland, NJ about 1968 (Figure 55). The quarry occupied a 55-acre tract 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 (Figure 54) 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 referred to as 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 the county park. This stop has been described in part by Olsen (1980b) and Olsen et al. (1989), and described in detail by Olsen (1995).

Although thousands of footprints have been found in the 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, Recreation and Cultural Affairs *Prospecting and collecting are no longer allowed at the Dinosaur Park without permission from the Center for Environmental Studies.*

The Towaco Formation at the Riker Hill quarry (the type section; Olsen. 1980a, c) 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.

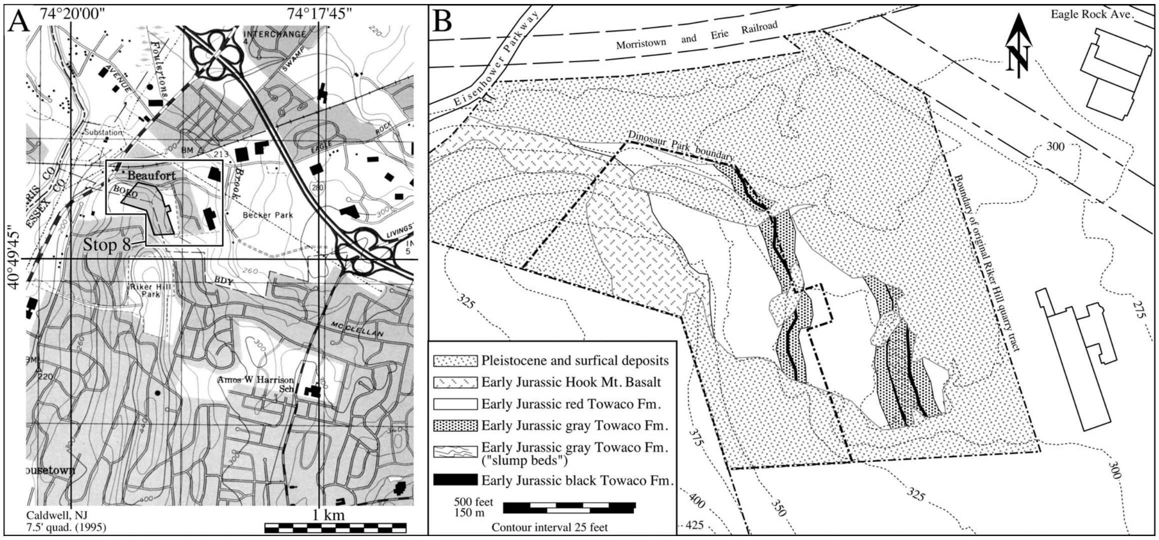

Figure 54. Walter Kidde Dinosaur Park, Stop 7, site maps: A, topographic map showing vicinity of park; B, geological map of park and surrounding area (from Olsen, 1985).

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 part of an entirely red fourth cycle (RVH-4) (Figure 56). Together, these cycles constitute most of a short modulating cycle (~100 ky duration). Presently, only the uppermost beds of RVH-3 and RVH-4 are exposed, representing less than ~40 ky of Jurassic sedimentation in the drying phase of a 100 ky short modulating cycle, which is in turn the drying phase of a 404 ky McLaughlin cycle, itself in the wet phase of a 1.75 my long modulating cycle (Figure 4). In the following description of the paleontology, all of the fossils will be keyed into the section shown in Figure 56 so their positions within the pattern of cyclically-shifting climate can be seen.

Varied assemblages of plant 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 body fossils have been found as well. As 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 insects, fish, plants, and pollen and spores 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 Kidde Dinosaur Park are trace fossils.

Pollen assemblages recovered from units 9-10are, as is typical for the Early Jurassic of tropical Pangea, dominated by the extinct conifer genus *Corollina* (*Classopolis*), accompanied by various other conifer, cycadophyte, and fern spores (Figure 57) (Cornet, 1977). Remains of cheirolepidiaceous conifers are the most common macroscopic plant fossils in all facies at Riker Hill. Compressed wood and fossil charcoal almost certainly belonging to these plants are found in all of the gray and black beds at the, and large roots are present in 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, 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 as footprints (Figure 57). *Imponoglyphus torquendus* was originally described from Late Triassic age strata of the former Soviet Union and an example of this form taxon has been described from Walter Kidde Dinosaur Park by Metz (1984). This form species consists of impressions resembling truncated cones fitted into one another. *Imponoglyphus torquendus* is almost certainly an impression of a conifer shoot similar to that shown in Figure 57. From the extreme dominance of the remains of cheirolepidiaceous conifers in all facies at the, both as macro- and microfossils, it is clear that the woodlands and scrub lands of the Newark basin in Towaco time were strongly dominated in biomass by the cheirolepidiaceous conifers. However, it is not yet possible to tell how many biological species of cheirolepidiaceous conifers are represented, and the species diversity could be quite low.

A rich invertebrate trace fossil assemblage has been recovered over the years from the Riker Hill quarry, mostly from strata exposed in Walter Kidde Dinosaur Park (Figure 58). As described by Metz (1992), *Cochlichnus anguineus* consists of smooth, narrow

Figure 55. Riker Hill Quarry (Stop 7) ca. 1969: a, contact between Hook Mountain Basalt (above) and Towaco Formation (type section); b, top of gray bed, unit 6; c, base of gray bed unit 15-16 (Figure 56).

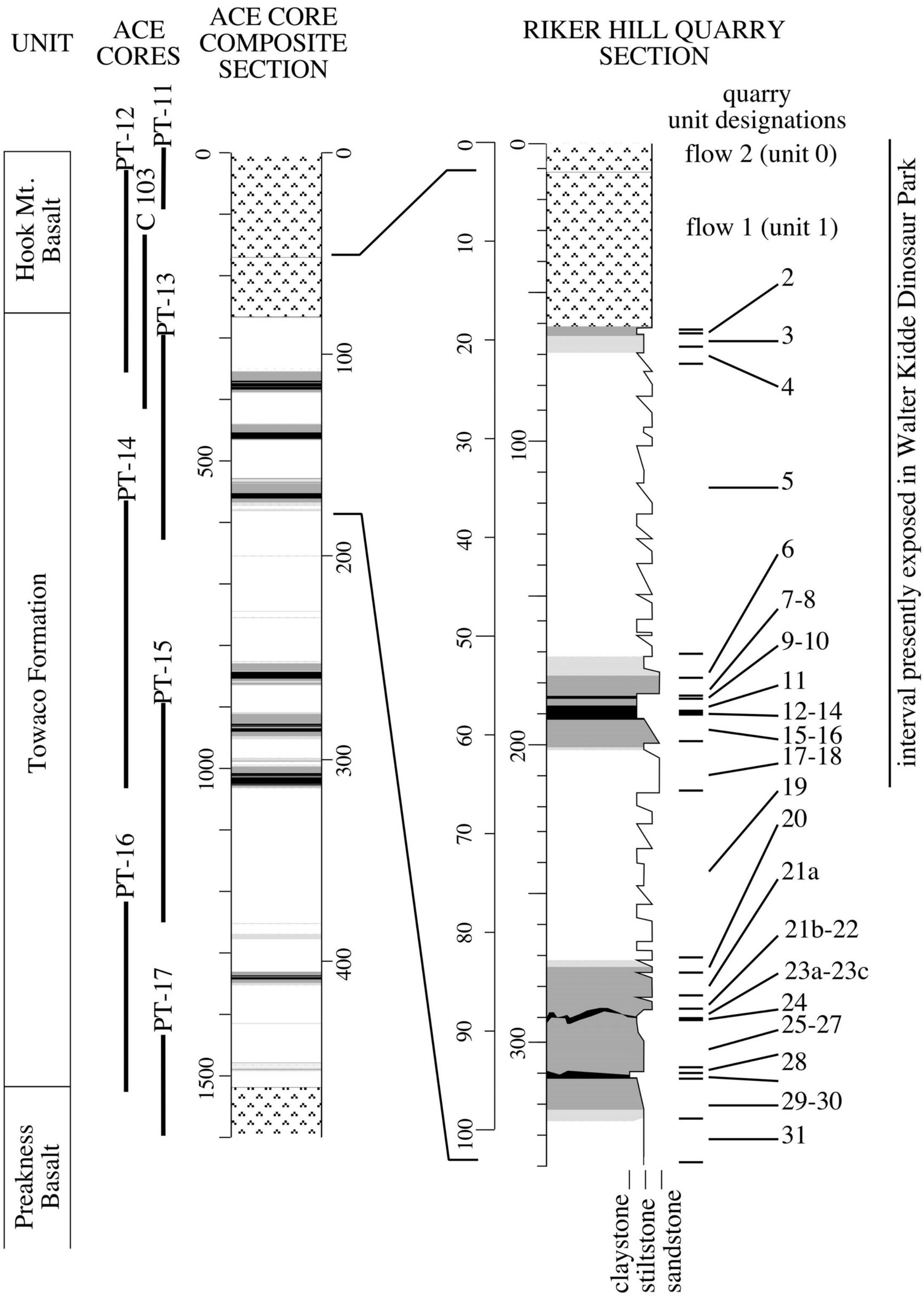

Figure 56. Figure 4. Section in old Riker Hill quarry compared to reference section of the Towaco Formation from the Army Corps of Engineers cores (Olsen et al., 1996b). Unit designations are referred to in text. Key to lithologies as in Figure 3. From Olsen (1995).

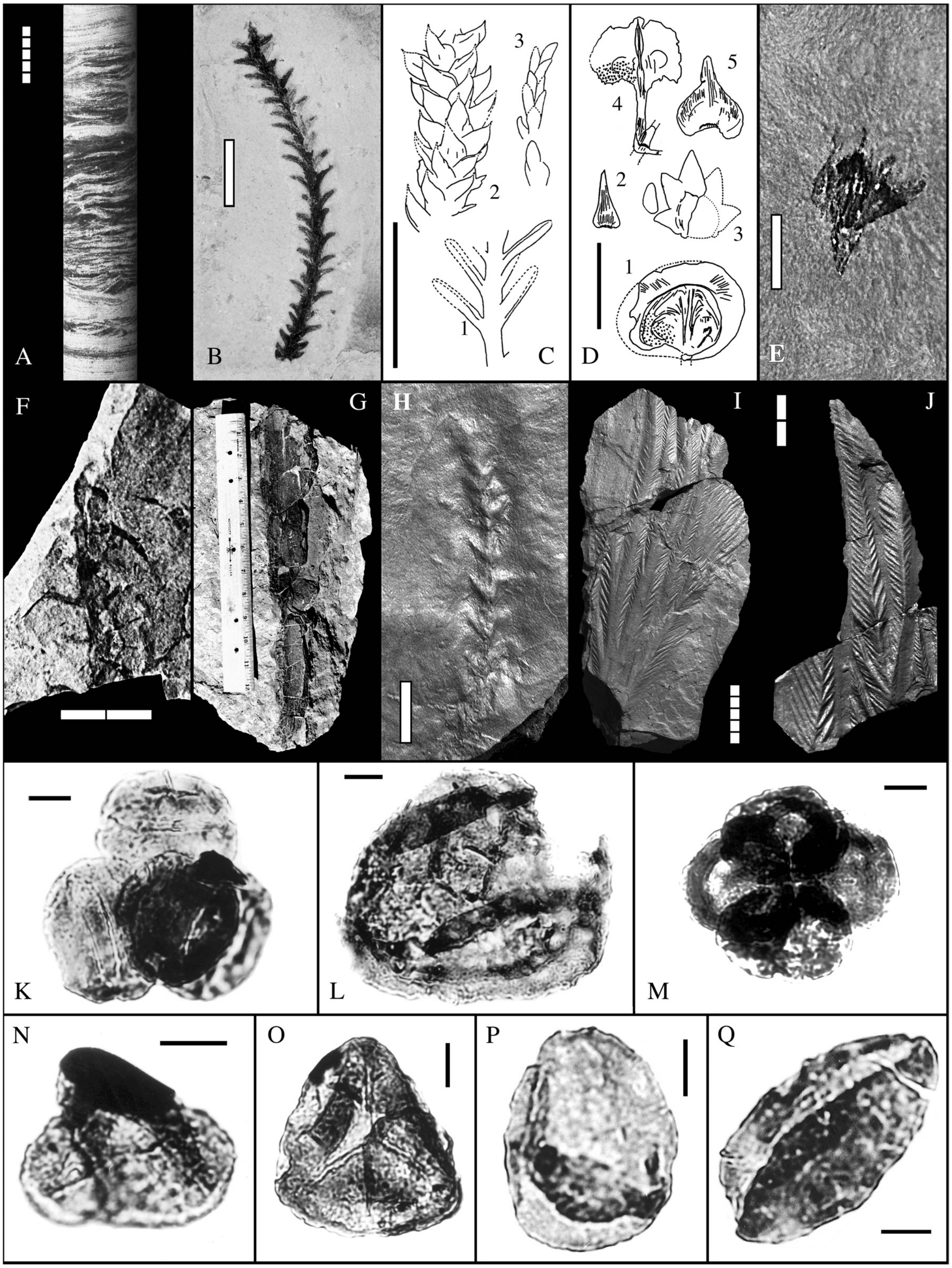
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Figure 57. Figure 6. Molecular and plant body (organ) fossils from the Riker Hill Quarry. **A**, Portion of Army Corps of Engineers core of the upper Towaco Formation showing oil staining in a pale gray fine rippled sandstone (molecular fossil) (scale, 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. From Olsen (1995).

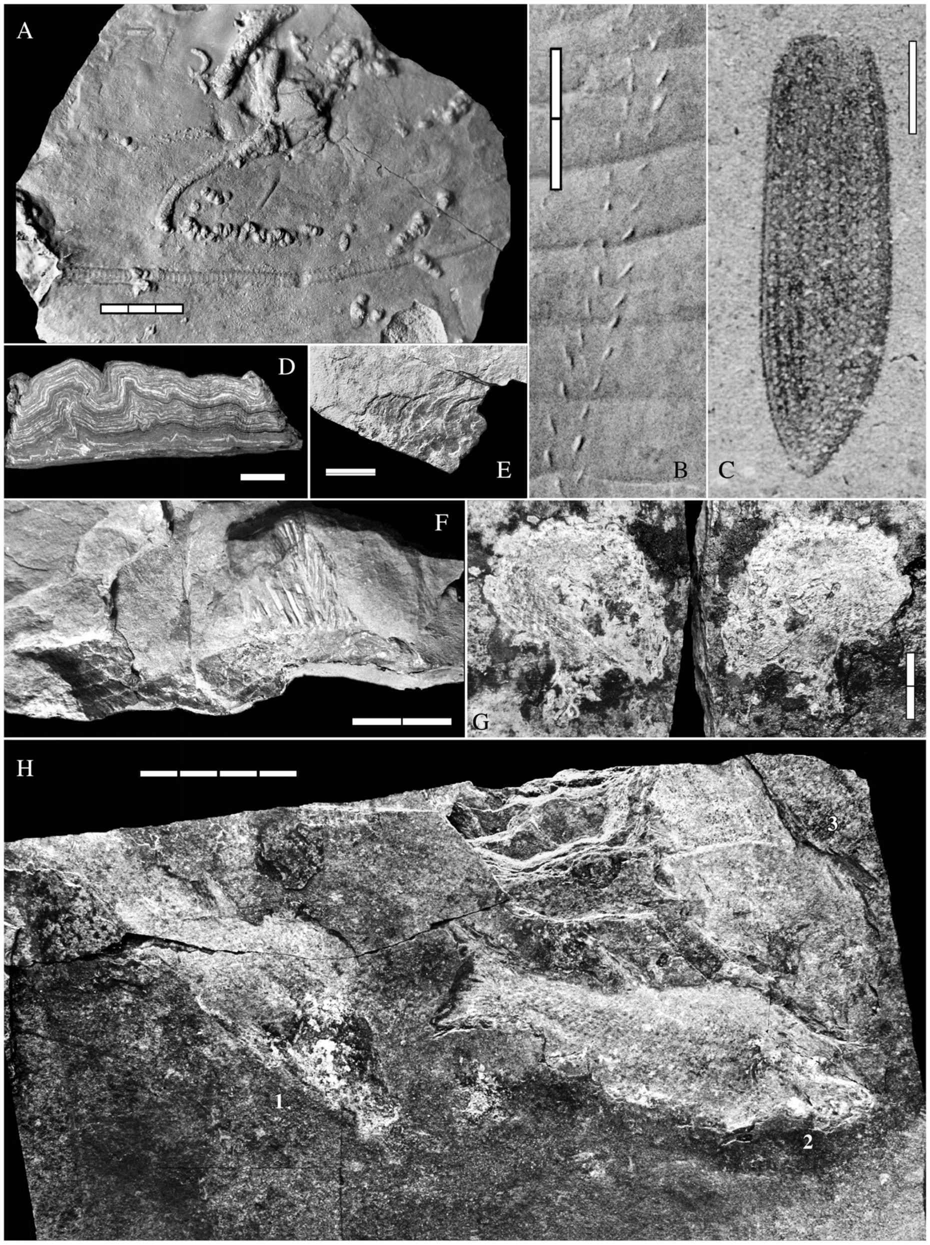

Figure 58. Invertebrates and fish from the Riker Hill Quarry. **A**, unusual, unidentified burrow (scale, 3 cm) from unit 5, Dinosaur Park; **B**, insect walking trace, *Acanthichnus* sp., from low in unit 5, Dinosaur Park; **C**, beetle elytron (wing cover), *Liassocupes* sp., unit 10, Dinosaur Park (specimen in YPM collection) (scale, 4 mm); **D**, Folded microlaminated D, folded microlaminated □-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 is of the *Semionotus tenuiceps* group, while the other two are indeterminate.

(1.5-2 mm), sinusoidal, unlined, and unbranching horizontal burrows possibly made by nematodes or perhaps fly larvae. *Helminthopsis* sp. (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 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 curved, 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 to *P. montanus*, but shows discontinuous rings where the burrow tapers (Metz, 1991). A perhaps similar form is shown in Figure 58; in this example a burrow which shows distinct annuli is present, 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 taxon with few defining characters, 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 zigzag pattern". The originator of this kind of trace is unknown. *Biformites* sp. and *Fustiglyphus roselandensis* are possibly related to *Trepyichnus* described by Boyer (1979) from the Riker Hill quarry. *Fustiglyphus* consists of two kinds of linked trails: a thin (0.4-0.6 mm) part 4-7 mm long with distinct annulae and a thicker (2-2.5 mm) part 2 to 3 mm long with faint annulae . There is a faint groove running down the middle of the trace. *Biformites* is a tapering trace with annulae 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 Walter Kidde Dinosaur Park, where it is not common. *Scoyenia* is a lined burrow with a meniscate 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 the Newark basin Jurassic, notably so in the Towaco Formation. There is little consensus on the makers of *Scoyenia* with opinions ranging from polychaete worms (D'Alessandro et al., 1987), to insects (Frey and others, 1984), and crayfish (Olsen, 1988). This taxon is very badly in need of detailed study.

Insect body fossils are represented by a single beetle elytron (wing cove) from unit 10. The narrow rows of punctures between ridges and the general shape of the elytron distinguishes the beetle family Cupedidae, hence the common name "reticulated" beetles. The elytron from Walter Kidde Dinosaur Park most closely resembles the Early Jurassic genus *Liassocupes* Whalley 1985 (Figure 58, Huber et al., 2002). The cupedids are often regarded as the most primitive of the beetle families. The family is extant; both the larvae and adults feed on rotting wood. *Cupes concolor* is the most common living member of the family in the United States and is very similar to the Walter Kidde Dinosaur Park fossil. This isolated elytron 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

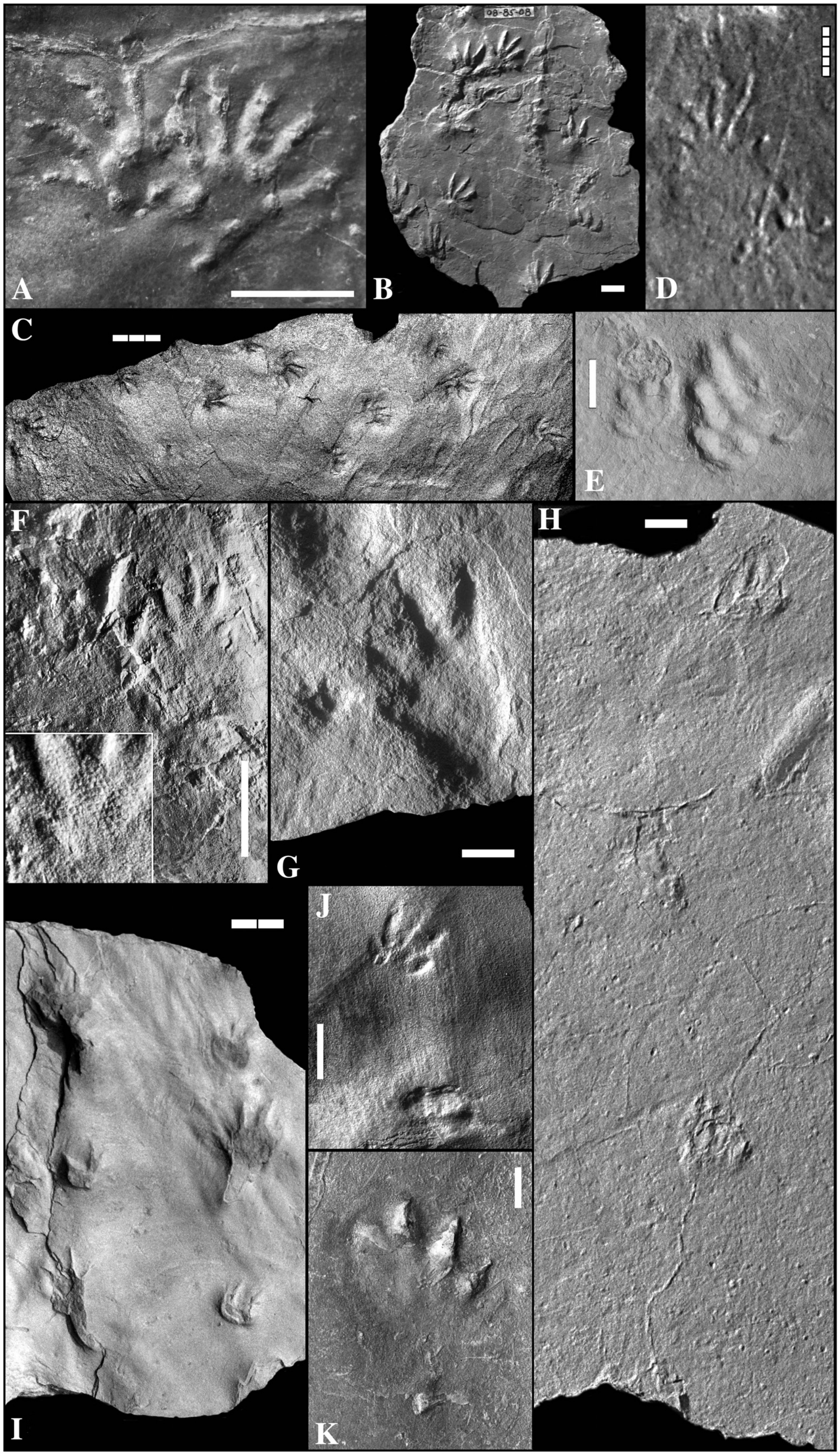
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Figure 59 Quadrupedal tracks from the Riker Hill quarry. **A**, Right manus-pes set of *Ameghinichnus* n. sp. from upper unit 5, Dinosaur Park (AMNH 29298, collected by Larry Felder, 1978). Manus is on left and pes is on right. **B**, Drawing of trackway of *Ameghinichnus* n. sp. Arrow shows manus pes set in A (above). **C**, Leptodactylus 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**, 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. E, manus pes set of Batrachopus deweyii, xxxx collection. **F**, 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. **G**, 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. **H**, Trackway of *Batrachopus* from same slab as Figure 62K, Riker Hill quarry, collector and disposition unknown (scale 1 cm). **J**, Manus and partial pes impression of *Batrachopus* sp. from unit 5, Dinosaur Park (Charles Rizzo collector, Charles Rizzo collection) (scale 1 cm). **I,** Very deep underprint of trackway of ?*Batrachopus* sp. from rubble, Riker Hill quarry (specimen lost). Note deep impression of heel area. **K**, *Batrachopus deweyii* pes from the Vreeland Quarry, stratigraphic equivalent to unit 5 at Riker Hill (Rutgers New Brunswick Museum main display slab) (scale 1 cm). Adapted from Olsen (1995).

due to both a real bias against fossilization as well as a collection bias. Recent years have seen a strong increase in the number of insect body fossil occurrences in the Newark Supergroup (Fraser et al., 1996; Huber et al., 2002; Olsen, 1988) and there is no reason not to expect more finds at Walter Kidde Dinosaur Park (especially with intense collecting of unit 10).

Several trackways attributable to *Acanthichnus* (Hitchcock, 1858) have been found at Walter Kidde Dinosaur Park (Figure 59). This ichnogenus is distinguished by two rows of thin impressions. These kinds of tracks could be made by any of a number of types of walking insects. The well-defined trackways shown in Figure 59 come from the lower part of unit 5, which has very small oscillatory ripples characteristic of very shallow water.

The only fish genus found thus far at the Walter Kidde Dinosaur 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 section (Fig. 4). Cycle RVH-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 RVH-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 part of unit 5).

In the entire Newark basin, the Towaco Formation 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 (1987, 1996) show 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 the laminated division 2 of a single Van Houten cycle. This type 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 a local deficit in the generic diversity due to geographic isolation.

At the Riker Hill quarry, at least three species of *Semionotus* appear to be present, although the preservation is too incomplete for certain identification (Figure 58). These are *Semionotus tenuiceps,* a small thin bodied form with small dorsal ridge scales, and a large form. *Semionotus tenuiceps* has a distinct hump at the back of the head and has 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 (Figure 58). Fish from unit 24 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 of calcium phosphate (hydroxylapatite). Generally, in the process of fossilization, the cellular spaces within the bone become filled with minerals - often calcite - introduced by groundwater; 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 phosphatic mineral matter of the bone has been dissolved away, leaving an outline marked by the residuum of the organic matrix of the bone and organic matter in the gut. This dephosphatization has been noted elsewhere in the Newark Supergroup and is generally more prevalent in the portions of lacustrine strata farther from the basin edge (McDonald and LeTourneau, 1989). 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 (Figure 58). In this case the bone tissue has been dissolved by 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 the lower part of 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 be the excrement of a small theropod dinosaur.

By far the most spectacular fossils found at the Riker Hill quarry are tetrapod footprints. Thus far, excellent examples of *Ameghinichnus*, *Batrachopus*, *Grallator*, *Anchisauripus*, *Eubrontes*, and *Anomoepus* have been found. Only one other ichnogenus is known from elsewhere in the Newark basin Jurassic - the lepidosauromorph track *Rhynchosauroides*.

Ameghinichnus was first found by Larry Felder in 1978, in the upper beds of unit 5 of Walter Kidde Dinosaur Park. The ichnogenus was established by Casamiquela in

1964 for small five-toed quadrupedal tracks from the Late Jurassic Matilde Formation of northern Santa Cruz province in Argentina. The Towaco form differs somewhat from *A. patagonicus* (Casamiquela, 1964) and we consider it to be a new (although unnamed) species. The genus is characterized by a pentadactyl manus and pes of equal size, with nearly symmetrically-disposed digits of subequal length (Figure 59). 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 *Ameghinichnus* ichnospecies) or trithelodonts (which were contemporaries of at least the Towaco ichnospecies). The size of the Towaco form is more consistent with trithelodonts or the largest of the Early Mesozoic mammals. Trithelodonts (e.g. *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 et al., 1987; Shubin et al., 1991). We therefore favor trithelodonts as the makers of the Riker Hill species of *Ameghinichnus*, although we cannot exclude other therapsids (including mammals) on the basis of existing evidence. Since the discovery by Mr. Felder, several more specimens of *Ameghinichnus* have been recovered from closely adjacent beds, although all of these are leptodactylous forms (Figures 26, 59). A complete treatment of this new species will be given elsewhere.

A single trackway found by John Colagrande in the uppermost Towaco Formation of Towaco, New Jersey represents the sole known post-Passaic Formation occurrence of *Rhynchosauroides* in the Newark Supergroup (Figure 59). It is described here because it should also occur at Riker Hill. During the Triassic, there were a very wide range of lepidosauromorph reptiles that could have made *Rhynchosauroides*-type footprints including the Trilophosauria, Rhynchosauria, Protorosauria, and the Lepidosauria, but by the Early Jurassic only the Lepidosauria remained. The Lepidosauria include the Rhynchocephalia (Sphenodontia; which includes the living *Tuatara*) and the Squamata (lizards and snakes). Small members of either group could have made these Jurassic *Rhynchosauroides*, although we note that an appropriate sized sphenodontian, *Clevosaurus bairdi*, is one of the most abundant skeletal forms known from the earliest Jurassic of Nova Scotia (Sues et al., 1994).

The probable-crocodylomorph track *Batrachopus deweyii* is the most common quadrupedal ichnite in the Newark Supergroup Jurassic, and is common at Walter Kidde Dinosaur Park as well (Figure 59). The form genus is diagnosed as a small quadrupedal form with a five-toed manus and a functionally four-toed digitigrade pes. Skeletal examples of crocodyliforms have been found in the Early Jurassic Portland Formation of Massachusetts (*Stegomosuchus longipes*; Walker, 1968) and the McCoy Brook Formation of Nova Scotia (*Protosuchus micmac*; Sues et al., 1996). The crocodyliforms of the earliest Jurassic, such as *Protosuchus*, were rather different in their overall appearance from living crocodilians (crocodiles and alligators). They were small, slender, short-snouted, and lightly armored, with no obvious aquatic adaptations. Their skeletons had 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 were digitigrade most of the time, while modern crocodilians walk plantigrade nearly all the time. In contrast to the large lunging semi-aquatic modern crocodilians, the makers of *Batrachopus* were small, fully terrestrial, active, fast predators.

By far the most abundant dinosaur tracks at the Riker Hill quarry are bipedal three toed forms (Figure 60) that never have manus impressions. The smallest ones (1.5-15 cm long) tend to be very narrow, with a distinctly elongate middle digit (III); the largest ones (20-30 cm long) 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 all proportions. These types of tracks have been traditionally called *Grallator* (the smallest forms), *Anchisauripus* (the intermediate-sized forms), and *Eubrontes* (the largest forms) (e.g. Lull, 1953). The phalangeal formula and general proportions are consistent with small to medium-large theropod dinosaurs. One would think that because these kinds of tracks are very common, they must be well known and understood; unfortunately the reality is a nomenclatural quagmire badly in need of revision.

This nomenclatural 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 the type specimens are not, and virtually every named taxon has a tortured and confused history (e.g. Olsen et al., 1998); even the commonly-used names are not necessarily valid by strict application of nomenclatural rules!. Second, organisms change in shape as they grow. This is termed "allometry" and is caused by different growth rates in different parts of the body, and we 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), essentially revisions of Hitchcock's monographs (1858, 1865). As defined by Lull's concept of their type species, the major differences between the genera *Grallator*, *Anchisauripus*, and *Eubrontes*, apart from size, are the ratio of length to width, the relative projection and length of digit III, and the angle of divarication between digits II and IV. When considering the type specimens (as identified in Lull, 1953) alone the genera appear morphologically quite

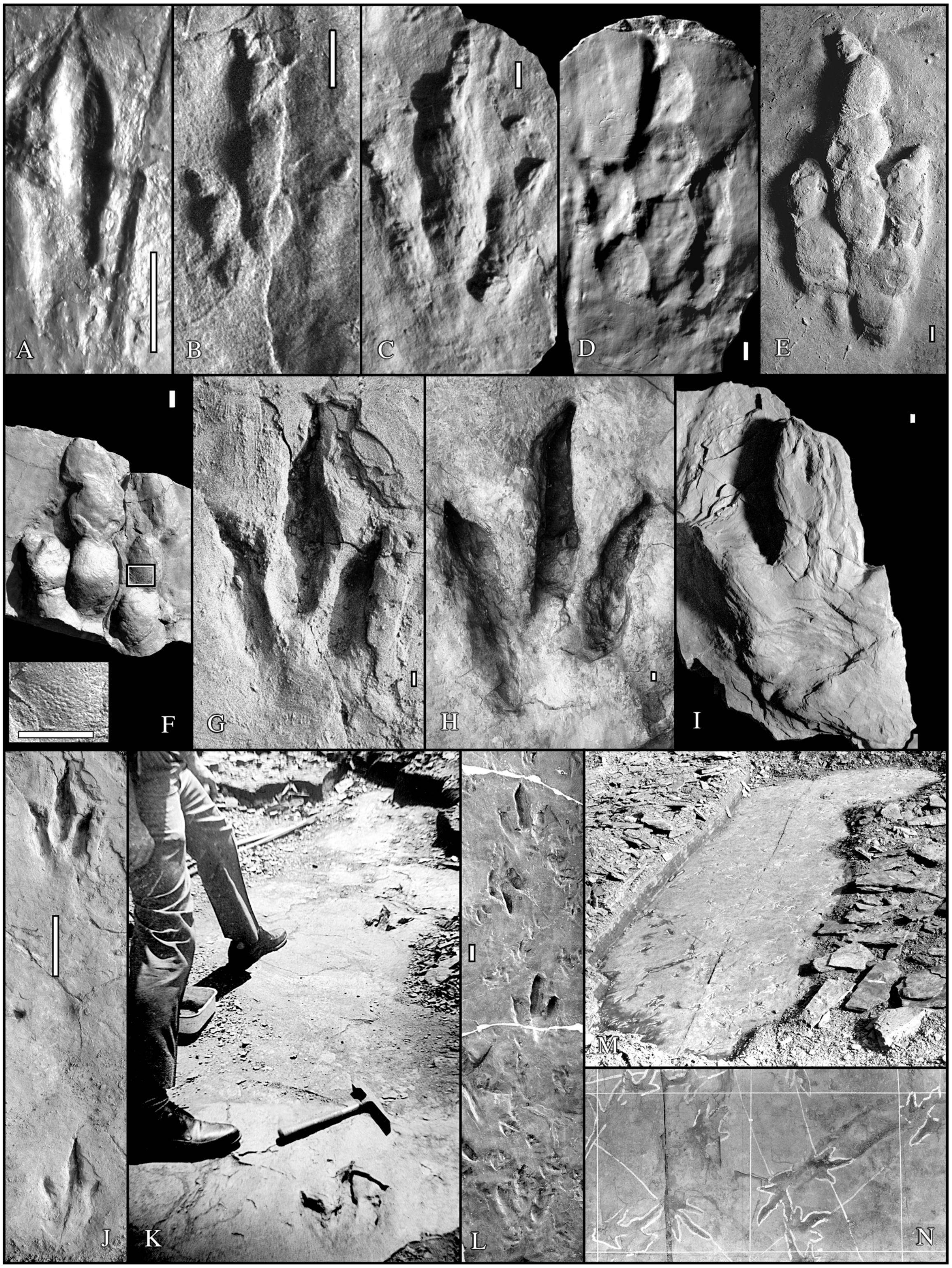
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Figure 60. Theropod dinosaur footprints from the Towaco Formation (mostly of the Riker Hill quarry). A, Natural cast of left pes of very small, Grallator (*Grallator*) sp., upper unit 18, Walter Kidde Dinosaur Park, John Colegrande collector, John Colegrande collection (same as Figure 10Aa and same slab as Figure 61C). **C**, Natural cast of left pes of *Grallator* sp., Riker Hill Quarry, ECPC 21; *Anchisauripus* sp., Riker Hill Quarry (Robert Salkin collector, Robert Salkin collection). **D**, Right pes of *Anchisauripus* sp., plaster cast of specimen, Riker Hill Quarry, AMNH 29299. **E**, Natural cast of left pes of *Anchisauripus* sp., upper unit 18, Walter Kidde Dinosaur Park, lost specimen. **F**, Natural cast of right pes of *Anchisauripus* sp., same trackway as E (above); note scale impressions in inset (specimen lost). **G**, Left pes of *Anchisauripus* sp., upper unit 18, Dinosaur Park, specimen not collected; same track as second in trackway in J (below). **H**, Left pes of *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 *Anchisauripus* sp., upper unit 18, Dinosaur Park, specimens not collected). **K**, *In situ* trackway of small *Eubrontes giganteus* sp., upper unit 18, Dinosaur Park, second track in series is ECPC 9. **L**, Trackway of *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. **N**, *Grallator* footprints on surface of unit 23c from slab shown in M (above).

distinct. However, when we attempt to place other specimens in these taxa we find that there are a multitude of intermediate forms. As suggested by Olsen (1980b) and Olsen et al. (1998), all of the forms lie on a morphological trend varying in a consistent way with size. It is not at all apparent to us that it is possible to objectively isolate portions of this trend as separate genera. As the size of the footprint increases, the relative width of the footprint increases, as does the divarication between digits II and IV; there is thus a decrease in the projection of digit III beyond the outer two toes. The same general proportional changes can be seen between the skeletons of the small ceratosaurian theropod *Coelophysis* (Colbert, 1989) and the much larger ceratosaur *Dilophosaurus* (Welles, 1984). The larger specimens of *Coelophysis* fit the proportions of large *Grallator* or small *Anchisauripus*. If these footprints cannot be objectively split up into several genera, they should all be give the earliest proposed valid name, which should be *Eubrontes* (Ornithichnites Hitchcock 1836) (Olsen et al, 1998). But, pending a revision of these genera (underway by ECR), we refer to them the same way as did Lull (1953): as *Grallator*, *Anchisauripus*, and *Eubrontes*, and collectively as grallatorids.

Among the many grallatorid tracks from Riker Hill are some very small examples (Figures 60). These tracks are among the smallest dinosaur footprints known from anywhere geographically and temporally. A nice gradational series of tracks intermediate between the smallest grallatorids and the largest *Eubrontes* have been found at the site (Figure 60).

Remains of small theropods have been found in Jurassic Newark Supergroup strata in the Portland Formation of Connecticut and Massachusetts and the McCoy Brook

Formation of Nova Scotia (Colbert and Baird, 1958; Olsen et al., 1987; Sues and others, 1987; Talbot, 1911). A single large tooth fragment found within a *Eubrontes* track at Walter Kidde Dinosaur Park (unit 18) is the only skeletal material of theropods yet found in the Newark basin (Olsen, 1995).

The ichnogenus *Anomoepus* (Hitchcock, 1848) is the only other common dinosaurian track form that has been positively identified from the Riker Hill quarry. This 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 than similar-sized grallatorids. Sitting traces are fairly common, in which the entire pes including the metatarsus is impressed, as is the five-toed manus. The wide range of sizes of *Anomoepus* present at Roseland demonstrate the range of variation in the genus, although there is far less variability than is seen in the grallatorid forms described above. We have not, however, found criteria for recognizing more than one footprint species, and therefore we synonymize all *Anomoepus* species from the Newark Supergroup with *Anomoepus scambus*, the type species of the genus from the Turners Falls Formation of Massachusetts (Olsen and Rainforth, 2002). 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 foot length.

The structure of the inferred pedal skeleton is compatible with either a theropod or an ornithischian dinosaur; however, the hand flatly rules out a theropod trackmaker, because all five digits remain well developed, albeit short. In contrast to theropods (in which manual digits I-III are dominant, IV and V eventually being lost), manual digits II-IV are dominant in *Anomoepus* - the beginnings of a trend seen clearly in more advanced ornithischians (e.g. hadrosaurs), in which the outer digits are reduced and finally lost. *Anomoepus* was therefore probably made by a small, herbivorous, relatively primitive ornithischian dinosaur, similar to *Lesothosaurus* or some other "fabrosaur". Scrappy bones and isolated teeth of "fabrosaurs" have been found in the McCoy Brook Formation of Nova Scotia (Olsen et al., 1987; Sues et al., 1987).

Anomoepus is characterized by a less well-developed pad structure in the pes than grallatorids. Although the skin texture is very similar to grallatorids, the pads tend to be separated by much smaller narrower pads, suggesting that 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 to be expected in a hand used more for grasping than walking. Thus, it seems likely that *Anomoepus* used its hands, and sometimes its feet, to grasp things - probably branches; a reasonable scenario for a small herbivorous dinosaur.

One of the most unusual aspects of the Riker Hill assemblages is the unusually large number of presumably-juvenile *Anomoepus* tracks. One layer in particular in the upper part of unit 18 was covered in many small and a few larger *Anomoepus*. The association of the uncommon larger forms with the much more abundant smaller forms suggests, but of course does not demonstrate, herding of young. The smallest *Anomoepus* tracks are, like the tiny *Grallator*, among the smallest dinosaur footprints known. Unfortunately, also like the tiny *Grallator*, these tracks lack pads and thus the assignment to *Anomoepus* can only be tentative. One of the minute *Grallator* trackways is from the same bedding plane as the abundant "baby *Anomoepus*". The meaning of the diminutive carnivore among the baby herbivores is unknown.

The track assemblage at Walter Kidde Dinosaur is typical for the Towaco Formation, and is very similar to all of the Newark Supergroup assemblages that postdate the Triassic-Jurassic boundary. They are the post-catastrophe assemblages, largely consisting of survivors of the end-Triassic mass extinction.

Return to Beaufort Avenue.

91.4 mi. Turn right onto Beaufort Avenue.

91.8 mi. Turn right onto Eisenhower Parkway.

92.4 mi. Turn left onto Eagle Rock Avenue.

93.1 mi. Crossing Passaic River.

93.8 mi. Turn right onto Ridgedale Road. This area is often flooded by waters from the Passaic River. Control of this flooding was the goal of the proposed Passaic River diversionary tunnel, the planning stages of which resulted in the collection of over 10 k of short cores (each ~<100 m) spanning the upper Passaic Formation and most of the succeeding Jurassic Formation (Fedosh and Smoot, 1988; Olsen et al., 1996b) collected by the Army Corps of Engineers (ACE cores).

95.2 mi. Turn right onto New Road.

96.1 mi. Turn right onto Bloomfield Avenue.

96.5 mi. Cut in Hook Mountain Basalt. Immediately north in the same ridge is the cut for Interstate Route 80 that comprises the type section of the Hook Mountain Basalt (Olsen, 1980c).

96.6 mi. Turn left onto Mountain Road.

96.7 mi. Turn right onto Maple Avenue

97.0 mi. Turn left onto entrance for Interstate Route 80 East.

102.9 mi. Gap in ridge for Preakness Basalt through which the Hudson River flowed.

104.8 mi. Crossing Passaic River.

106.1 mi. Gap on left in Orange Mountain Basalt for Hudson River.

106.3 mi. On right are outcrops of the Orange Mountain Basalt and underlying uppermost Passaic Formation. This is section E of the type section of the Passaic Formation of Olsen (1980c). A series of faults cut the Orange Mountain Basalt here, some of which are visible in the cut on the left, just west of the Passaic - Orange Mountain Basalt contact. Triassic-Jurassic boundary is somewhere within a few meters below contact.

107.1 mi. Garrett Mountain visible on right (south), Passaic Falls is on the left (north). The upper Passaic Formation of Rhaetian age (latest Triassic) has produced near here a series of well preserved skeletons of the highly specialized procolophonid reptile Hypsognathus (Colbert, 1946) including the type specimen, which was found just south of here (Gilmore, 1928). About one skeleton or skull is found in the northern Newark basin per decade.

108.8 mi. Section D of type section of Passaic Formation (Olsen, 1980a,c).

112.6 mi. Section C of type section of Passaic Formation (Olsen, 1980a,c).

113.7 mi. Section B of type section of Passaic Formation (Olsen, 1980a,c).

116.8 mi. Beginning of type section of Passaic Formation (section A, Olsen of Olsen, 1980a,c) in open cuts for Route 80.

116.1 mi. Merge with Interstate Route 95.

118.7 mi. Open cut in Palisade sill and Lockatong hornfels. According to Van Houten (1969), hornfels include grosularite, andradite, prehnite, and diopside varieties. Lockatong cycles fossiliferous, as usual, and these cycles may tie in with Granton Quarry cycles (Stop 4). Geochemistry of the sill at this cut described by Naslund (2000).

119.3 mi. Exit left for US Route 9W and Palisades Interstate Parkway.

119.6 mi. Turn left onto US Route 9W north and follow along the creast of the strikeridge of the Palisade sill.

120.1 mi. Keep left on US Route 9W north.

130.6 mi. Lamont-Doherty Earth Observatory. End of Field Trip. End of Fieldtrip.

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