Field Guide for Non-marine Boundary Events in the Newark Basin (New Jersey, Pennsylvania, and Connecticut), Eastern United States and their Litho-, Chrono- and Biostratigraphic Context.

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ABSTRACT

This field guide is intended to familiarize participants of IGCP 458 with the aspects of the Newark and Hartford rift basins relevant to the non-marine Triassic-Jurassic boundary and its larger context. We will visit 27 stops that illustrate these the basins' range of sedimentary and igneous environments and paleobiological assemblages, focusing on their significance to the understanding of global events around the Triassic-Jurassic boundary.

INTRODUCTION

The Newark and Hartford basins (Figures 1, 2) are parts of the remarkable series of early Mesozoic rift basins that extend from Greenland to Europe, Morocco and eastern North America, and to the Gulf of Mexico. This massive set of basins - the central and north Atlantic margin rifts - formed during the crustal extension that led to the fragmentation of Pangea (Figure 3). The Newark and Hartford basins are among 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), and which were apparently formed in entirely non-marine settings. 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 and Hartford basins - 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 3). This field guide, based largely on two previous guides (Olsen et al., 1989; Olsen and Rainforth, 2002b), is meant as a basis for discussion of topics related to the Triassic-Jurassic boundary and IGCP Project 458 - Tr-J Boundary Events.

TECTONOSTRATIGRAPHY, CYCLOSTRATIGRAPHIC FRAMEWORK, AND STRATIGRAPHIC NOMENCLATURE OF THE NEWARK AND HARTFORD BASINS

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 4). 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). There is, however, no evidence for TS II in the Hartford 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. TS IV is well represented in the Newark and Hartford basins, especially in the latter, where more dated Jurassic strata are preserved than elsewhere in eastern North America.

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 4). 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 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. 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. In the case of the Newark basin, TS III and IV are well developed Schlische cycles, while in the Hartford basin TS III is entirely fluvial and only TS IV displays a full Schlische cycle, - albeit an excellent one.

We hypothesize that 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. On the other hand, there is substantial evidence of a composite unconformity at the TS III-IV boundary in the Hartford basin, which at least locally cuts out the Triassic-Jurassic boundary, although the correlative conformity is probably preserved over much of the basin. The differences may be due to greater depth of erosion within the Newark, relative to the Hartford basin.

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 5).

Precisely the same kind of lacustrine cyclicity seen in the Newark basin pervades the lower three quarters of TS IV in the Hartford basin. While understood in broad outline for decades (Hubert et al., 1976), the detailed pattern of this cyclcity has been worked out only in recent years as a result of detailed field work and study of industry and Army Corps of Engineers cores (Kent and Olsen, 1999a; Olsen et al., 2002d, e).

Based on these cores as well as outcrop studies, one of the most dramatic features of the Newark and Hartford basin sedimentary record is the pervasive cyclicity obvious in most of the sequence (Figure 6). 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).

In the Newark basin, the thickness of Van Houten cycles varies from about 1 meter to over 25 meters, depending on both the geographic and stratigraphic position in the basin. There is less variation in thickness in the Hartford basin, with the total range being between 10 and 30 m, again depending on stratigraphic and geographic position. Within single formations in specific areas of the basin, the thickness tends to vary only about 25%.

The Van Houten 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 6).

Within the Newark basin, obvious asymmetrical sequences of the Van Houten cycle are observed. These depositional sequences on one end typify 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 this “aridity gradient”, even within the same more complete stratigraphic sections, red massive sandstone dominates the Van Houten cycle. . 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 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 relative wetness or dryness of Van Houten cycles is modulated by three orders of cycles, producing a characteristic and predictable pattern (Figure 6). 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 mark 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). The 3.5 my long modulating cycle, as seen in the Newark lithostratigraphy, is called the Laskar cycle (Olsen and Rainforth, 2002b).

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 <u>thickness</u> 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 <u>time</u> 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), and earliest Jurassic (with data added from the Hartford basin), which is pinned in absolute time by radiometric dates from CAMP igneous rocks (Figure 5). 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 and Hartford basin sections have been divided into formal lithostratigraphic mappable formations (Figures 5) that generally do not correspond to the tectonostratigraphic divisions (Figures 4, 5) (Kümmel, 1897; Olsen, 1980a; Olsen et al., 1996a; Krynine, 1950; Lehman, 1959). In the Newark basin, 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 lacustrine and marginal lacustrine 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 lacustrine and marginal fluvio-lacustrine 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 red and gray mostly lacustrine and marginal fluvio-lacustrine clastic sequence with distinctive basal set of three black, gray, and red Van Houten cycles, lower and upper of which have significant limestone beds, followed by less obviously-cyclical mostly-red mudstone, sandstone and minor conglomerate (maximum thickness >120 m) (Olsen, 1980a; Olsen et al., 1996a, b); 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 lacustrine and marginal lacustrine 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 5). 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 5).

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 (and Hartford basin, below) 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 unique character (Figure 5). 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.

The Hartford basin section is divided into seven formations, parallelto the Newark basin (Figure 4) (Krynine, 1950; Lehman, 1959). Indeed, the cyclostratigraphy of the upper six formations are virtually identical to the temporally overlapping portions of the Newark basin. These are, in ascending stratigraphic order: the New Haven Formation, consisting nearly entirely of fluvial tan, and red sandstone and conglomerate, and red mudstone, with very minor gray clastic rocks red eolian sandstone (maximum thickness ~2250 m); the Talcott Basalt, which consists of a complex of high titanium quartz normative (HTQ) tholeiitic basalt flows and associated volcanoclastic beds (maximum thickness > 100 m) (Emerson, 1898; Rogers et al., 1959; Lehman, 1959; Sanders, 1970; Puffer et al., 1981; Philpotts and Martello, 1986); the Shuttle Meadow Formation, which consists of a mostly lacustrine and marginal fluvio-lacustrine clastic red, gray and black sequence very closely comparable to the Feltville Formation, although with better developed cyclcity (maximum thickness > 100 m) (Krynine, 1950; Lehman, 1959; Olsen et al., 1996b); the Holyoke Basalt, made up of two major flows of high iron quartz normative (HFQ) basalt (maximum thickness > 100 m) (Emerson, 1898; Rogers et al., 1959; Lehman, 1959; Sanders, 1970; Puffer et al., 1981; Philpotts, 1992); the East Berlin Formation, comprised entirely of cyclical lacustrine and marginal fluvio-lacustrine red, gray, and black mudstone, sandstone and conglomerate, and minor limestone (maximum thickness >150 m); the Hampden Basalt, made up of two major flows of high titanium, high iron, quartz normative (HFTQ) basalt and its volcanoclastic equivalent in the northern Hartford basin, the Granby Tuff (maximum thickness >60 m) (Emerson, 1898; Rogers et al., 1959; Lehman, 1959; Sanders, 1970; Puffer et al., 1981; Philpotts, 1992); and finally the Portland Formation, composed of a lower half consisting of lacustrine and marginal fluvio-lacustrine red, gray and black clastic rocks closely comparable to the Easter Berlin Formation, and an upper half made up almost entirely of fluvial red mudstone sandstone and conglomerate and minor red eolian strata (total maximum thickness ~5000 m).

Olsen et al. (2002d) propose to divide the lower Portland Formation into members in a parallel manner to the Passaic Formation of the Newark basin. They recognize four full McLaughlin cycles in the lower Portland, and one continuing from the underlying East Berlin Formation. These mappable units are proposed as members as follows (from the bottom up): "Northampton", "East Granby", "South Hadley Falls", "Mittinegue", and "Stony Brook" members. These units are critical to establishing the cyclostratigraphy and time scale for the Hettangian and Sinemurian sites and hence reconstructing the sedimentologic and structural history from the Triassic-Jurassic boundary.

SUMMARY OF BASIN TECTONIC HISTORY

It is becoming increasingly clear that the latest Paleozoic and Mesozoic tectonic history of eastern North America, namely the type “Atlantic passive margin” Newark and Hartford basins, is much more complicated than previously thought (e.g. Malinconico, 2002; Olsen, 1997; Schlische, 2002; Wintsch, 1997; Withjack et al., 1995, 1998). It has long been realized that regional extension followed the late Paleozoic compressive and oblique assembly of Pangea relatively quickly . 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 reactivatedappropriately-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 3).

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, although according to Wintsch (1997) uplift continued well into the Creaceous in the Hartford basin. Northwest-southeast compression slowed sometime in the Cretaceous or Cenozoic and 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 AND HARTFORD BASIN AND THEIR DEPOSITIONAL ENVIRONMENTS AND PALEONTOLOGY

Tectonostratigraphic Sequence I

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

Tectonostratigraphic Sequence II

In the Newark basin, all of the Stockton Formation below the Cutaloosa Member appears to belong in TS II (Figures 5). 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 7). 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 4). There is likewise no evidence of TS II in the Hartford basin and TS III apparently laps directly onto basement rock.

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 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 expressions 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. 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 of 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 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 **Error! Bookmark not defined.Error! Bookmark not defined.**), 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 **Error! Bookmark not defined.Error! Bookmark not defined.**). 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, an 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. For the most part, the Passaic continues the cyclical pattern found in the Lockatong (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 the 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) larvae. Fish are much more rare in the Passaic Formation than in the Lockatong Formation. This correlates both with decreased frequency of microlaminated strata as well as insufficientprospecting. 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 other 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.

TS III is also very widespread in the Hartford basin, where it consists completely of the New Haven Formation. It differs dramatically from the Lockatong and Passaic formations of the Newark basin in that there is virtually no evidence of lacustrine strata. Instead, TS III consists of red and tan fluvial strata, the stratigraphy and age of which is relatively poorly known. The basal New Haven formation locally has beds of gray sandstone that at one locality (Forestville, CT: Krynine, 1950; Cornet, 1977) has produced a palynoflora closely comparable to that of the lower Passaic Formation and hence conventionally assigned a basal Norian age (Cornet, 1977). The rest of the lower New Haven Formation consists of cyclical fluvial strata that have been interpreted as meandering river sequences (McInerney, 1993; Horne et al., 1993). These have common and locally very well developed pedogenic soil carbonates, one of which has provided a U-Pb date of 211.9 ± 2.1 Ma from pure pedogenic micritic calcite (Wang et al., 1998), which is a Norian age on most time scales, including that from the Newark (Gradstein et al., 1995; Kent and Olsen, 1999). The same exposure has produced a partial skull of the crocodylomorph *Erpetosuchus*, which is otherwise know from the Lossiemouth Sandstone of Scotland, conventionally given a Carnian age (Olsen et al., 2000b). Previously described reptilian skeletal material from the lower New Haven Formation in the southern Hartford basin comprises the holotype of the stagonolepidid *Stegomus arcuatus* Marsh, 1896. Lucas et al. (1997) considered *Stegomus* to be a subjective junior synonym of *Aetosaurus* and uses *Aetosaurus* as an index fossil for continental strata again suggesting an early to middle Norian age, although this has been questioned (Sues et al., 1999).

The middle New Haven Formation consists of mostly red massive sandstone with much less well developed pedogenic carbonates (Krynine, 1950). There have been virtually no studies of this part of the formation. Apart from abundant *Scoyenia* burrows and root casts, the only fossil from the middle of the Formation is a scapula of an indeterminate phytosaur ("*Belodon validus*" Marsh, 1893), of no age significance, save indicating a probable Late Triassic age.

Much more varied lithologies categorize the upper part of TS III and upper New Haven Formation (Hubert, et al., 1978), including meandering and braided river deposits and minor eolian sandstones (Smoot, 1991). Vertebrates from these strata include an indeterminate sphenodontian (Sues and Baird, 1993) and the procolophonid *Hypsognathus fenneri* (Sues et al., 2000). The presence of *Hypsognathus* indicates correlation to the upper Passaic Formation of the Newark basin and thus a later Norian or Rhaetian age.

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 little 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). 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 <u>well below</u> 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 5). 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 palynomorphs which fall into two groups, permitting 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 exceeds about 60% of the assemblage). Strata of the upper Exeter Township Member and the remainder of TS IV lack Triassic taxa 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 *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 TS IV the Newark basin are virtually absent. Thus far there are only a few bone flakes in a coprolite, and a shard of a large tooth, probably of a theropod dinosaur, from the natural cast of a *Eubrontes giganteus* footprint (Olsen, 1995)!

The Hartford basin TS IV is, as previously described, extremely similar to that in the Newark basin. There are some significant differences, however, in the lowermost and upper parts of this tectonostratigraphic sequence. The uppermost New Haven Formation makes up the lowest portions of TS IV. Markedly cyclical lacustrine strata appear to be lacking, and in many respects the uppermost New Haven strata resemble the uppermost Passaic Formation in the northern Newark basin, where there is some evidence of a TS III-TS IV hiatus (see above). At least locally there are gray plant and pollen-bearing ?marginal lacustrine strata just below the Talcott basalt (Heilman, 1987). The uppermost few centimeters of gray mudstone and sandstone preserve abundant *Brachyphyllum* shoots and cones and a palynoflorule of typical Early Jurassic aspect, dominated by *Corollina* (Robbins, quoted in Heilman, 1987). Because there is no dispute that most of the New Haven Formation is of Late Triassic age, the Triassic-Jurassic boundary probably lies either within the gray sequence below the conifer bearing level, or closely underlying it in the red beds, or it is cut out by a TS III – TS IV tectonostratigraphic hiatus.

There is one locality in the Hartford basin, however that bears at least a superficial similarity to the Triassic-Jurassic boundary in the Jacksonwald syncline. This is the *Clathropteris* fern locality in Northampton, MA (Cornet, 1977; Cornet and Traverse, 1975). This sequence consists of gray clastic rocks with an interbedded carbonaceous layer (in this case consisting of *Clathropteris* and the horsetail *Equisetites*) overlying a white to gray clastone, containing predominately fern spores and *Corollina*. There is no Talcott basalt in this area, and there are virtually no surrounding outcrops, so that the section is floating stratigraphically, although clearly in the equivalent of the uppermost New Haven or basal Shuttle Meadow formations. It is tempting to speculate that this might represent another boundary section, but clearly much more evidence is needed to falcify or support this possibility.

Above the uppermost New Haven Formation, generally fossiliferous cyclical lacustrine sequences dominate sedimentary sections of TS IV until the middle Portland Formation. Microfloral assemblages are present in most gray claystonnes and siltstones and in all cases they are dominated by Corollina (Cornet, 1977). Floral macrofossils are often present in the same units. Assemblages bearing *Clathropteris* and *Equisetites* are common in the Shuttle Madow Formation and equivalents and the upper of the limestone bearing cycles in the lower part of the formation has produced a relatively diverse macroflora of ferns, cycadeoides, ginkophytes, and cheirolepidaceous conifers (Newberry, 1888). Floral assemblages from the East Berlin and Portland Formations tend to be much more dominated by cheirolepidaceous conifers, notably *Brachyphyllum* and *Pagiophyllum* and their reproductive structures (Cornet, 1977).

Invertebrates are represented in TS IV not just by common burrows, but also locally by abundant clams, ostracodes, conchostracans, and insects (McDonald, 1992; Huber, et al., 2002).

Articulated fossil fish, often beautifully preserved and very abundant, occur in microlaminated portions of specific Van Houten cycles in TS IV of the Hartford basin, just as they do in the Newark basin and include the same genera (Olsen et al, 1982). The youngest fish-bearing sequence in the Portland Formation (Chicopee Fish Bed of the “Mittinegue” member) is dominated by a form unkown elsewhere in the Newark Supergroup called *Acentrophorus chicopensis* (Newberry, 1888) that, although abundant, is unfortunately poorly preserved, and in reality generically indeterminate.

TS IV of the Hartford basin is the type area of the famous Connecicut Valley footprint assemblage (e.g. Hitchcock, 1836, 1848, 1858, 1865; Lull, 1904, 1915, 1953; Olsen et al., 1998; Olsen and Rainforth, 2002a), the taxonomy of which is massively oversplit and confused. However, these assemblages, like those of TS IV in the Newark basin (above the

Triassic-Jurassic boundary) are dominated by dinosaur tracks, particularly grallatorids (theropod dinosaur tracks including *Grallator*, *Anchisauripus*, and *Eubrontes*). Other dinosaurian forms present include *Anomoepus* (Lull, 1953; Olsen and Rainforth, 2002a) and *Otozoum* (Lull, 1953; Rainforth, 2002). There is no obvious difference from the oldest to youngest assemblages.

Osteological remains from TS IV are almost compeletly limited to the upper, fluvial part of the Portland Formation. Several localities have produced fragmentary to nearly complete skeletons of the prosauropod genera *Anchisaurus* and *Ammosaurus* and the crocodylomorph genus *Stegomosuchus* (Lull, 1953). Marginal lacustrine or fluvial intervals within the cyclical lower Portland have produced a single small theropod skeleton (*Podokosaurus*) found in a glacial boulder (Lull, 1953) and a natural cast of an impression of a fragmentary small theropod skeleton (Colbert and Baird, 1958). In addition, two isolated probably theropod teeth have been found in the lower Shuttle Meadow Formation (McDonald, 1992).

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, 1999b; 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 of 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 penecontemporaneous with the three largest Phanerozoic flood basalt provinces. For each of these three flood basalt occurrences, there is at least some evidence of an asteroid or comet impact. Boslough et al., 1996 has proposed a mechanism linking bolides with flood basalts,but the energetics have yet to be reconciled with the observations and the models (Melosh, 2000). Nonetheless, it seems plausible that a massive impact might be able to initiate volcanic eruptions by concentrating the effusive rate of a distant flood basalt province. 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 associated lower temperatures for a period of months. At least in the case of the Triassic-Jurassic boundary, a significant time of elevated CO_2 followed (McElwain, et al., 1999), culminating in a rise in global temperatures. The effects of the meteoritic impact,post-impact widespread lightning-induced fires,and the resultant cold combined to increase the amplitude of the massive ecological disruption. 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.

FIELD TRIP AND ROAD LOG

The field stops are organized in three basic swaths in four days, designed to focus on the environmental and temporal context of the Triassic-Jurassic boundary. The stops are divided into four days, with the Day 1 concentrating on the northern Newark basin and the Triassic and Jurassic sections, including the CAMP basalts and intrusions. The stops on Day 2 look primarily at the cyclcity of Triassic and very earliest Jurassic lacustrine strata in the central and southwestern Newark basin and the Triassic-Jurassic boundary. Day 3 looks at Triassic and Jurassic cyclicity and environments and the Triassic-Jurassic boundary in the Newark and Hartford basins predominately from core. Stops on Day 4 examine the Hartford basin Triassic and especially Jurassic section where it is unusually well exposed.

DAY 1. NORTHERN NEWARK BASIN

Stop 1.1. 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 13). 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 (Figure 1).

Ministop 1.1a: Stockton Formation Alpine Boat basin: latitude 40°56.76'N, longitude 073°55.13'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 1g (see below), rather than a lateral equivalent of the Lockatong Formation as seen at higher elevations (Stops 1b-1f). 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 1g.

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 1g. To our knowlege these have not been prospected for vertebrates, or studied.

Head south on Henry Hudson Drive.

Stop 1.1b: 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 14). 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 15), 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.

Stop 1.1c: 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 **Error! Bookmark not defined.**). 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 16).

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 17). 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 18). 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 19). 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 20, 21, 22). 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. 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. 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 sun's bi-annual passage over the equator (Crowley et al., 1992; Olsen and Kent, 2000). 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, 22), 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 20).

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 18). In addition, the degree of lamination is generally less. The average thickness of the Van Houten cycles at this stop 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 17).

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 17, 23). 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 20).

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.

Ministop 1.1d: 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 24). 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.

Stop 1.1e: 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 25). 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.

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 do not know what cycle is represented by this exposure.

Proceed south along Henry Hudson Drive.

Ministop 1.1f: 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 26). 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.

Stop 1.1g: 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 27).

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 27). 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.), although it is actually from Edgewater

The specimen (AMNH 4991; Figure 27) 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.

Mini Stop 1.1h: Rotten olivine zone: latitude 40°50.798'N, longitude 073°57.882'W. Weathering profile of the olivine zone can be clearly seen here. The olivine zone is weathered to a very crumbly diabase, that according to Naslund (1998) still has much fresh-looking olivine crystals.

Stop 1.2. 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. <u>The</u> 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 1). 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 22). 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 28), 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 28).

Cycles G3 and G7 (Figure 28) 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.Many important fish and unique reptile skeletons have been discovered here by dedicated amateurs who donated their specimens to various museums through the years (Colbert, 1965, 1966; Colbert and Olsen, 2001; Olsen et al., 1989; Schaeffer, 1952; Schaeffer and Mangus, 1971). Undoubtedly 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 22). Larger remains occur as well, of which the most spectacular is the skull of a juvenile rutiodontine phytosaur (Figure 22), but isolated phytosaur bones and teeth are fairly common and an isolated vertebrae of a metoposaur amphibian has 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 from a few thousand years (within one Van Houten cycle) to over 1 million years (i.e. three McLaughlin cycles) (Figure 13).

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, 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 contain 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 lower 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 20). 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). Fish diversity cyclicity is a consequence of shoreline proximity. Proximity to shore, a function of depth, 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, 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 depend 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 initiated 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 nonetheless 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 created by turbulent stratification under conditions of relatively high primary productivity and low organic consumption (e.g. low ecosystem efficiency). The generally low organic content of divisions 1 and 3 of Van Houten cycles 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 purposes) 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. Without an appropriate model of why extra effort should be expended in those specific units, they get short shrift from the collector because of abundant fish occurrences 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 22) 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 20) 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 its dip slope, consists of arkosic tan sandstones, overlain by black shales (probably representing much of the remainder of the Lockatong Formation), which are in turn overlain by red mudstones of the Passaic Formation (Parker, 1993). If we assume an 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 is 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 movementoccurred 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.

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). The geochemistry of the sill at this cut is described by Naslund (2000).

Stop 1.3. 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 the long modulating cycle P4. The most eastern gray and purple unit probably is the lower part of the Kilmer Member (Figure 5).

Stop 6 is located on the eastern side of this ridge (Figure 1) and exposes the uppermost part of member T-U and the lower half of the Kilmer Member (Figure 29). 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 distinctive that during mapping of this member its surface trace became known as the "dead zone" because the copper-rich regolith limits plant growth. . There is surficial evidence of copper prospect pits where an unnamed brook crosses the Kilmer Member in Piscataway (NJ), but these are not mentioned by either Lewis (1907) or Woodward (1944).

In the outcrops in the northeastern Newark basin, the same Van Houten cycle apparently lacks black shale. Instead it has 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 29).

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 in the vicinity 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 30). 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

Return to Polito Avenue and turn left, heading north.

Stop 1.4. I78 cut in Orange Mountain Basalt: Springfield, New Jersey (optional)

Latitude and Longitude: 40° 42' 33"N, 74° 20' 01"W
Tectonostratigraphic Sequence: TS IV
Stratigraphic Unit: Orange Mountain Basalt
Age: Early Hettangian; 202 Ma
Main Points:

1. Oldest flow sequence of CAMP in superposition to Tr-J boundary
2. HTQ basalt, similar to chill zone of Palisades sill
3. Columnar jointing and pillowed zones
4. Valley to northeast water gap for ancestral Hudson River

The Orange Mountain basalt is a quartz normative tholeiitic basalt in Puffer and Lechler's (1980) hight titanium group (HTQ) which lies along the Palisades sill fractionation trend. It is dark-greenish-gray to black, fine-grained, dense, hard basalt composed mostly of calcic plagioclase and clinopyroxene. Locally the basalt is vesicular contains small spherical to tubular gas-escape vesicles, often filled with zeolite minerals or calcite, typically above base of flow contact. The total thickness of the flow sequence is about 127 m, with three major flows present separated in places by a weathered zone, a bed of thin reddish-brown siltstone, or by volcaniclastic rock, as well as vesicular zones often more than 2 m thick. The lower part of the upper flow is locally pillowed while the upper part has pahoehoe structures. The middle flow is massive to columnar jointed. The lower flow (characteristic of these exposures) is generally massive with widely spaced curvilinear joints and is locally pillowed near the top.

There is a deep buried valley to the immediate northeast. The elevation of bedrock in that valley is at sea level, 30 m below the lower parts of the present valley. According to Johnson, 1981, this was water gap and channel for the ancestral Hudson River, which flowed east here after coursing though another gap in the Preakness basalt ridge, and the western side of Riker Hill (Hook Mountain Basalt – Stop 1.7). We will see much better exposures of this basalt at Stop 1.8.

Stop 1.5. I78 cut in Upper Feltville Formation and Preakness Basalt: Short Hills, New Jersey (optional)

Latitude and Longitude: 40° 42' 33"N, 74° 20' 01"W
Tectonostratigraphic Sequence: TS IV
Stratigraphic Unit: Upper Feltville Formation and Preakness Basalt
Age: Early Hettangian; 202 Ma
Main Points:

1. Second flow sequence of CAMP
2. HFQ basalt
3. Distinctive splintery fracture
4. Thickest known single cooling unit in CAMP
5. First significant CAMP sedimentary interbed (Feltville Fm.)
6. Fluvio-deltaic and shallow water lacustrine facies of Feltville Fm.

About 10 m of upper Feltville Formation and 30 m of lower Preakness Basalt are exposed at this road cut on the north side of Interstate Route 78. The upper Feltville at this outcrop consist of tan to pink sanstones and red mudstones. The sandstones and siltstones typically show climbing ripple crosslamination arranged in tilted beds (relative to regional bedding) that toe downward into red mudstones, comprising small delta forsets. Mudstone drapes between beds often have mudcracks, as do the mudstones at the toes of sandstone beds, illustrating at least occasional dessication. The scale of the forset beds suggests maximum water depths on the scale of a few meters. There are also dinosaur tracks in some of the red ripple crosslaminated siltstones.

The overlying Preakness basalt is a dark-greenish-gray to black, fine-grained, dense, hard basalt composed mainly of intergrown calcic plagioclase and clinopyroxene, most of which falls into into the high iron quartz normative (HFQ) basalt group of Puffer and Lechler (1980). There are three main flows within the Preakness basalt separated by vesicular zones more than 2 m thick as well as a red mudstone unit between the lower two flows. The maximum thickness of the entire Preakness flow sequence is about 320 m.The lowest flow is the thickest (>100 m) and has a massive lower colonnade with subtle large columnar joints, passing upward into the splintery (prismatic) fracture characteristic of the entablature of the lowest flow of the formation, as seen here and further west along I78 (Faust, 1977). These basalt splinters make up radiating slender columns 5 to 65 cm. wide. The middle flow is more massive and often has curvicolumnar jointing. The upper flow tends to be massive with some columnar jointing, but is of different composition namelyPuffer and Student's (1992) low titanium quartz normative (LTQ) basalt. We will see better exposures of the Preakness basalt at Stop 1.7.

Stop 1.6. Limestone-bearing Van Houten cycles at the base of the Feltville Fm., Watchung Reservation, old village of Feltville, Union County, NJ.

Latitude and Longitude: (aprox.) 40°40.78'N, 74°23.15'W
Tectonostratigraphic Sequence: TS IV
Stratigraphic Unit: Uppermost Orange Mt. Basalt and Feltville Formation
Age: Early Hettangian; 202 Ma

Main Points:

1. Upper flow of Orange Mt. Basalt and contact with Feltville Fm.
2. Wet maximum of next 100 ky cycle after Triassic-Jurassic boundary
3. Distinctive limestone-bearing Van Houten cycles of lower Feltville
4. *Clathropteris* (fern) in growth position with dinosaur tracks
5. Species flocks of Semiontid fishes

The lower Feltville Formation and its contact with the underlying Orange Mountain basalt is exposed in a series of outcrops in the gorge of Blue Brook in the Watchung Reservation. These outcrops show the two limestone-bearing Van Houten cycles and intervening gray shale-bearing Van Houten cycle typical of the sediments just above the oldest basalt sequence in eastern North America (Figure 31). This section comprises the type section of the Formation (Olsen, 1980a).

Originally, based on widely scattered small outrops, I (Olsen, 1980a, b) thought there was but one limestone-bearing sequence in the lower Feltville Formation and that it was subject to large scale lateral variations in facies and thickness. That two cycles are present became obvious only with the initial description of the first series of ACE cores (Fedosh and Smoot, 1988; Olsen et al., 1996a, b). The pattern was subsequently confirmed in superposition outcrop by more persistent field work (including minor excavation) at the type section and elsewhere (Figure 31). Another supposition of mine that proved erroneous was that the two limestone-bearing sequences were each assumed to be a division 2 of two successive Van Houten cycles. Even in 1980 it was evident, however, that there was a significant gray shale interval between what proved to be the two limestone-bearing cycles at the outcrops at Feltville, and when cores from the lower Shuttle Meadow Formation of the Hartford basin became available, it became obvious that this gray shale interval was in fact a division 2 of a complete Van Houten cycle, albeit not a particularly calcareous one sandwiched between the two limestone-bearing cycles. In addition, the uppermost limestone-bearing cycle has two deeper water intervals. Finally, looking at all of the major outcrops of the lower Feltville, it becomes clear that from northeast to south west the cyclical lower part of the Feltville thins and onlaps onto the Orange Mountain Basalt with an eventual loss of the red beds below the lower limestone-bearing cycle and loss of the intervening gray shale-bearing cycle (Figure 31).

The Van Houten cycles of the lower Feltville are clearly similar in their basic vertical transitions in facies to Van Houten cycles at the maxima of short modulating (~100 ky) and McLaughlin (404 ky) cycles in the Passaic and Lockatong Formations (Olsen, 1980b), although, the thickness of the lower Feltville Van Houten cycles is two to three times greater than those of the underlying formations. The proximally succeeding red beds are therefore the sediments deposited in the drier phases of the short modulating cycle. Gray sandstone and gray and purple mudstone beds occur in the uppermost Feltville Formation. In the middle Feltville there are several vague purplish and greenish beds. I believe these to be several poorly expressed Van Houten cycles marking the wet phases of two successive short modulating (~100 ky) cycles. Thus, in total, the Feltville formation consists of the upper three-quarters of a McLaughlin cycle (404 ky cycle), the basal quarter of which is the Exeter Township Member of the Passaic Formation (see Stop 2.7). However, the detailed pattern of the cyclicity is not as regular as that seen in underlying or overlying formations. Perhaps this is due to interference of the 40 ky obliquity cycle, a long term effect of whatever caused the Triassic-Jurassic boundary, or an effect of the initial transgression of the Tethys into the rift zone of Morocco, Iberia, and the Scotian and New Foundland shelves.

Both the Feltville Formation of the Newark basin and the coeval Shuttle Meadow Formation of the Hartford basin, as well as correlative strata of the Culpeper and Deerfield basin are characterized by the presence of common well-preserved occurences of the fern *Clathropteris meniscoides*, often preserved in growth position. Such an example was found at these outcrops in a gray climbing ripple crosslaminated siltstone and fine sandstone in the transgressive part (division 1) of the lower limestone-bearing Van Houten cycle (Figure 32) directly associated with dinosaur footprints preserved in *Leptodactylus* mode (see below).

As described for Stop 2.7, spores of *Clathropteri*s (*Granulatisporites infirmus*; Cornet and Traverse, 1975) are the dominant palynomorph in the fern spike at the Triassic-Jurassic boundary. Additionally, *Clathropteri*s is abundant at the single post-boundary macrofossil in the uppermost Passaic Formation, where it lies at the base of the youngest level of abundant earliest Jurassic reptile tracks (see Stop 2.7). *Clathropteri*s is markedly less abundant andmuch less well preserved in other formations in the Newark Supergroup. Presumably this has something to do with the climatic (CO_2?) or physiographic milieu (relief?) of the time of the Triassic-Jurassic boundary and the initial extrusions of the CAMP.

Reptile footprints are relatively common at this site and in the Feltville in general and occur in a variety of lithologies, showing a range of footprint preservational styles (Figure 33). Tracks are found as lower-relief natural casts and impressions in flaggy sandstones and siltstones, as faint underprints, and as leptodactylous forms (Figure 34). 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 my 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, as in the Feltville Formation, 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).

Fossil fish occur in both limestone laminite intervals in the lower Feltville Formation. Only three genera have been found thus far: the holostean *Semionotus* (Figure 35), the two palaeonisciformes, *Redfieldius* and *Ptycholepis*. While hundreds of *Semionotus* have been found, only a few fragmentary specimens of the other two genera have been identified. It is very unusual for lakes, especially large ones, to have this few genera, and other genera are probably present but in low abundance. Studies of thousands of well-preserved *Semionotus* from the Newark Supergroup Jurassic by McCune (1987, 1996) show that although diversity at the genus-level is very low, at the species-level,diversity may be very high, numbering in the tens or even hundreds of species (Figure 36). 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 genetic diversity due to geographic isolation. However, in the Newark Supergroup evidence of fish species flocks is entirely limited to to strata interbedded with or closely overlying the CAMP lava flows, at perhaps some other factor is in play, related to events around the Triassic-Jurassic boundary, such as the extinction of all Newarkian aquatic carnivores. In any case, it is clear from the study of modern species flocks that the evolution of even hundreds of species can occur within thousands of years in “empty” new environments, such as the Great Lakes of East Africa (Johnson et al., 1996) or their Jurassic analogs of the Newark Supergroup that we see here.

Stop 1.7. 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 37), was first reported in the local newspapers of Livingston and Roseland, NJ about 1968 (Figure 38). 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 recognized for its abundant reptile footprints, and in 1971 the owners agreed to give the most fossiliferous portion of the tract to the Essex County Department of Parks and Recreation. The resultant 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 38) 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.

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 39). 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 5). In the following description of the paleontology, all of the fossils will be keyed into the section shown in Figure 39 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 9-10 are , dominated by the extinct conifer genus *Corollina* (*Classopolis*), accompanied by various other conifer, cycadophyte, and fern spores (Figure 40) (Cornet, 1977), as is typical for the Early Jurassic of tropical Pangea. 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 bedsand 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 40). *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 interfingering one another. *Imponoglyphus torquendus* is almost certainly an impression of a conifer shoot similar to that shown in Figure 40. From the extreme dominance of the remains of cheirolepidiaceous conifers in all facies as both macro- and microfossils, it is clear that the biomass of cheirolepidiaceous conifers strongly dominated the woodlands and scrub lands of the Newark basin in Towaco time.. 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 41). As described by Metz (1992), *Cochlichnus anguineus* consists of smooth, narrow (1.5-2 mm), sinusoidal, unlined, and unbranching horizontal burrows possibly made by nematodes or perhaps fly larvae. *Helminthopsis* sp. (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 41; 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 hodgepodge taxon with few defining characters, that could have been made by a 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 41; 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 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 41). 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 42 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*, and as is the case for the Feltville Formation, a species flock is be present. 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 41). 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. Studies of thousands of well-preserved *Semionotus* from the Towaco Formation of Pompton (NJ) by McCune (1987, 1996) show the presence of over 30 species of *Semionotus* in the laminated division 2 of a single Van Houten cycle (Figure 36).

Preservation of the *Semionotus* at the park is variable (Figure 41). 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 41). 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 the 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 42). 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 33 33, 42). 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 42). 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 42). 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 43) 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 muddle 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 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 given the earliest proposed valid name, which should be *Eubrontes* (Ornithichnites Hitchcock 1836;Olsen et al, 1998). Pending a revision of these genera (underway by ECR), we refer to them in the manner of Lull (1953): *Grallator*, *Anchisauripus*, and *Eubrontes*, and collectively as grallatorids.

There are some very small examples among the many grallatorid tracks from Riker Hill (Figures 4343, 44). 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 43).

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 (Figures 43, 45). 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 (Figures 43, 45). 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, 2002a). Also unlike *Grallator*, there seems to be little derivation 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 (Figure 45) 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 abnormally large number of presumably-juvenile *Anomoepus* tracks (Figure 45). One layer in particular in the upper part of unit 18 was covered in many small and a few larger *Anomoepus* (Figure 45). 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 in Figure 44 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.

Stop 1.8. Cut for I280 in Preakness Basalt: type section of formation.

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 46). 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 aerial 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).

Stop 1.9. Cut for I280 in Orange Mountain Basalt: type section of formation.

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 47) (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 curve 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).

The first exposures of Passaic Formation to the east (on the south side of the highway) 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.

Further to the east at the underpass for North 6th Street, on the north side of the highway, 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.

DAY 2. CENTRAL AND WESTERN NEWARK BASIN

Stop 2.1. Quarry in Prallsville Member of the Stockton Formation: TS II, Prallsville, NJ.

Latitude and Longitude: (aprox.) 40°48.92’N, 74°19.55’W
Tectonostratigraphic Sequence: TS II
Stratigraphic Unit: Stockton Formation
Age: Carnian; ~230 Ma
Main Points:

1. Fluvial part of TS II
2. Thick upward-fining cycles
3. Heavy bioturbation by *Scoyenia* and roots.
4. Dry phase of Laskar cycle

The Skeuse family quarry in upper part of the Prallsville Member of the Stockton Formation exposes about 60 m of section and begins about 760 m above the base of the formation (Van Houten, 1969, 1980). We will examine a 18 m section in the most recently active part of the quarry (Figures 7, 48).

The Stockton Formation comprises the oldest fill in the Newark rift basin and it is almost entirely fluvial in outcrop. Based on correlation with the Princeton no. 1 core Newark Basin Coring Project the Prallsville Member is within the upper part of TS II, and this exposure is within the drier phase of Laskar cycle LaT1. Based on the Newark basin time scale (Figure 48) the age of these outcrops should be 230 Ma.

Thick (~15 m) fining upward cycles are obvious here, which consist of, from the bottom up: 1) pebbly trough cross bedded sandstone at base passing upwards into sandy compound cross-bed sets - units tend to be kaolinized and have small to large siltstone rip-up clasts; 2) thick interval of well sorted sandstone with climbing ripple cross lamination and planar lamination with bioturbation and siltstone partings increasing up section; 3) climbing ripple to massive siltstone with intense bioturbation by *Scoyenia* and roots, and slickensided dish structures. The 18 m section exposed in the part of the quarry we will visit (main quarry - Figure 48) exposes almost a complete cycle plus the basal portion of a succeeding cycle.

The sequence of structures in these fining-upward sequences are consistent with large, perennial meandering or anastamosing river deposits. In addition, lateral accretion surfaces of point bars are suggested by the lateral fining of cross-bedded structures in the up-dip direction. The large river systems implied by these outcrops are incompatible with a closed basin model for the Newark basin (Smoot, 1985) and may indicate an open basin for this part of the basin's history. This is in accord with the predictions of the basin filling model outlined by Schlische and Olsen (1990) and Olsen et al. 1998) for the tripartite sequence comprising TS II.

Stop 2.2. Classic section of the Lockatong Formation (TS III), Rt 29, Byram, NJ.

Latitude and Longitude: (aprox.) 40°26.08’N, 75°03.67’W
Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Lockatong Formation
Age: Carnian; ~219 - 221 Ma
Main Points:

1. Longest exposure of Lockatong Formation

2. Best outcrop example of Milankovitch forcing
3. Central Newark basin faces
4. Four 404 ky cycles
5. Full range of environments and fossils seen in Lockatong

Exposed along the east side NJ 29 and along the ravine at its north end are more than 400 m of middle Lockatong Formation (Figure 49), which represents a shallower portion of the "deep lake" stage of TS III. This section comprises the dry part of Laskar cycle LaN2 (3.5 m.y. cycle) and the wet part of long modulating cycle L2 (1.75 m.y. cycle). These are the exposures on which Van Houten (1962, 1964, 1969) based most of his original interpretations and the exposures most often seen by visiting geologists. About 99% (405 m) of this section consists of fine calcareous mudstone and claystone with the remaining 1% (5 m) consisting of very fine sandstone. These exposures include the Ewing Creek, Byram, Skunk Hollow, and Tohicken members. McLaughlin's (1944) "First Thin Red" makes up the upper part of the Skunk Hollow Member and the "First Thick Red" makes up the upper part of the Tohicken Member.

This is certainly the best outcrop to see the style of Milankovitch cyclicity present in the Newark basin. These are also the lacustrine exposures most often seen by visiting geologists, although they are becoming increasingly overgrown in recent years. The stratigraphic interval represented by these exposures is represented in the Nursery no. 1 core of the Newark Basin Corning project (Figure 49). Although the accumulation rate is quite a bit lower at the Nursery site, the correlation with these exposures is unambiguous and the frequency properties of the core and exposure sections are very similar (Olsen and Kent, 1997).

In order to illustrate the wide range of variation exhibited by these cycles, we will compare two end-members of the range of sequences of sedimentary fabrics present in this section (Figure 50). These two end-members correspond, in part, to .Van Houten's (1962, 1964, 1969 detrital and chemical short cycles. Figure 50A shows a single Van Houten cycle in the lower part of the Skunk Hollow Member, which includes the Skunk Hollow Fish Bed, the most fossiliferous cycle exposed in this outcrop. Division 1 is a thin sand overlain by thin-bedded mudstone with an upward increase in total organic carbon (T.O.C.). This represents the beginning of lake transgression over the mostly dry playa flat of the preceeding cycle and this is followed by deposition under increasing water depth.

Following a pattern seen in many of the Late Triassic-age Van Houten cycles from several basins (e.g. Olsen et al., 1978; Olsen et al., 1989), the transition into division 2 is abrupt and is marked by the development of microlaminated calcareous claystone consisting of carbonate-rich and carbonate-poor couplets, averaging 0.24 mm thick. The basal few couplets of this interval contain articulated skeletons of the aquatic reptile *Tanytrachelos*, infrequent clam shrimp, and articulated fossil fish (*Turseodus* and ?*Synorichthys*). Abundant conchostracans occur in the middle portions of the unit. In its upper part, the microlaminae are very discontinuous, perhaps due to microbioturbation. No longer microlaminated, the succeeding portions of division 2 become less organic carbon-rich and less calcareous upward, and there is an upward increase in pinch and swell lamination. Deep, widely-spaced, sinuous desiccation cracks propagate down from the overlying unit. The average T.O.C. of division 2 (83 cm thick) of this cycle is 2.5%, a rather common value for black siltstones and limestones of the Lockatong. Studies of similar microlaminated units in other parts of the Lockatong suggest deposition in water in excess of 100 m deep, below wave base, and in perennially anoxic water (Manspeizer and Olsen, 1981, 1984a).

Division 3 is characterized by an overall upward increase in the frequency and density of desiccation-cracked beds and a decrease in thin bedding. Reptile footprints (?*Apatopus*) are found near the middle of the sequence. T.O.C. decreases through division 3 and is low (1.3%-0.5%). This interval shows the greatest evidence of subaerial exposure in the cycle and represents the low stand of the lake. However, as evidenced by the relative rarity of desiccation-cracked intervals and the generally wide spacing of the cracks themselves, submergence was much more frequent than emergence during deposition.

Figure 50B shows a Van Houten cycle in McLaughlin's "First Thin Red" about 55 m above the cycle shown in Figure 50A. This cycle contrasts dramatically with the Upper Skunk Hollow Fish Bed in consisting of 75% red massive mudstone and completely lacking a black organic carbon-rich division 2. Division 3 of the previous cycle (also mostly red) consists of red, massive, almost homogeneous-appearing mudstone with a faint but highly vesicular crumb fabric, which according to Smoot and Olsen (1985) formed by repeated desiccation of slowly aggrading mud in a playa lake, with the vesicular fabric representing air bubbles trapped in sediments during floods and hardened by desiccation. The vesicles do not seem to be related to an evaporitic texture.

The overlying massive mudstone of division 1 is gray and contains a better-developed crumb fabric. This unit was probably deposited under much the same conditions as the unit underlying it. Its iron was reduced, however, by the interstitial waters from the lake which deposited the overlying gray unit. The transition from an aggrading playa to a short-lived perennial lake is marked by an upward increase in lamination, a disappearance of the crumb fabric and a decrease in the density of desiccation cracks.

Division 2 of this cycle consists of red and green laminated to thin-bedded claystone lacking desiccation cracks. This is the lake's high stand deposit of this cycle and is most comparable to the fabric seen in the lower part of division 3 of the cycle shown in Figure 50A.

Division 3 consists of massive mudstone (argillite) sequences consisting of a basal green-gray mudstone grading into a very well-developed breccia fabric (Smoot and Olsen, 1985) and then upwards into a well-developed crumb fabric. Breccia fabrics consist of densely-spaced anastomosing cracks separating non-rotated lumps of mudstone showing some remnant internal lamination. They are very common in the Lockatong Formation and are directly comparable to fabrics produced by short periods of aggradation separated by longer periods of desiccation and non-deposition (Smoot and Katz, 1982). The breccia fabric passes upward into a well-developed vesicular crumb fabric. The transition into the overlying similar sequence is abrupt. These thin sequences, several of which here make up division 3 of a Van Houten cycle, are very common in the fine-grained facies of the Newark Supergroup.

The upper half of these thin sequences are cut by dish-shaped, concave-upward clay-lined surfaces with radial slickensides. These "dish structures" were described by Van Houten (1964, 1969) and interpreted as a possible gilgai-type soil feature (Van Houten, 1980). A mechanical analysis of these structures suggests they are coulomb fractures produced in relatively rigid, but not lithified, mud by more or less isotropic expansion (Olsen et al. (1989). The volume increase was probably due to eolian deposition of mud in desiccation cracks followed by rewetting. Because the bed was confined laterally, it fractured along listric, dish-shaped faults and compensated for increased volume by increasing in thickness. As a mechanical consequence of volume increase, the dish-structures are probably not specific to any particular environment in a larger sense, but could be indicative of a limited range of environments in a particular basin setting such as the Lockatong (J. Smoot, pers. comm.).

Clearly, this particular Van Houten cycle represents the transgression and regression of a lake which never became as deep as the cycle shown in Figure 50A and when lake level dropped, the lake desiccated for longer intervals. Unfossiliferous here, cycles of this type contain clam shrimp in division 2 and sometimes abundant reptile bones in division 3 in coarser facies. Most of the other cycles at this stop fall somewhere between these two extremes.

At the north end of the exposure is a creek with excellent outcrops of an additional 100 m of section of the upper Tohicken and lower Prahls Island Member (Figure 49).

Stop 2.3. Member C and Warford Member of the Passiac Fm., near Tumble Falls, NJ.

Latitude and Longitude: (aprox.) 40°27.62’N, 75°04.00’W
Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Passaic Formation
Age: latest Carnian; ~217.5 Ma
Main Points:

1. Long exposure of lower Passaic Formation
2. Mostly red, but still shows Milankovitch cyclicity
3. Central Newark basin faces
4. Two 404 ky cycles

The transition from Lockatong to Passaic Formation is marked by an increase in proportion of red massive mudstones over gray. The cyclical pattern remains intact through the transitions and through the entire Passaic Formation, however, the frequency with which deep lakes appeared was waning. These outcrops are the lowest in this part of the basin in which red rather than gray massive mudstones are dominant. The section illustrates the facies typical of much of the shallower lake phase of TS III within the Newark basin.

Exposed along the east side NJ 29 are about 100 m of lower Passaic Formation (Figure 51) showing the classic cyclical alternation of thin black and gray shales and mudstones and much thicker packages of red mudstone. Outcrops on the southwest side of Devils Tea Table and Cains Run are of the gray and black portions of Member C, the lowest of many 404 ky year cycles in the Passaic Formation. The dominant lithology in the gray beds is a massive mudcracked mudstone (breccia fabric) deposited in a playa. However, gray and black more fissilemudstones deposited in perennial lakes occur about every 5-7 m, outlining the same kind of cyclicity seen in the underlying Locktatong Formation (Stop 2.2).

The thick sequence of red mudstones higher in Member C still follows this pattern, although the gray and black units are replaced by fissile red or purple siltstones (Figure 51).

Member C falls within the driest phase of long modulating cycle L3 and the dying part of Laskar cycle LaN3. We will walk west along the exposures of member C to Warford Brook, which has excellent exposures of the lower part of the next McLaughlin cycle the lithostratigraphic counterpart of which is the Warford Member. Although the general trend though the Passaic Formation is an upward decrease in the frequency of thick black shales deposited by deep lakes, well-developed black shales do periodically occur. One such unit occurs in the gray part of the Warford Member where one Van Houten cycle has a black and dark gray shale unit over 4 m thick, the basal part of which is very finely laminated and contains whole fossil fish (Figure 51). This part of the Warford Member was traced by McLaughlin (1945) 11 km to the northeast into conglomerates and to the Chalfont fault, 30 km to the west. Recent mapping shows that this unit can be traced 20 km more to the west to Limerick, PA. and 55 km to the east to New Brunswick, New Jersey (Olsen et al., 1996a). The Warford Member falls within the wet phase of long modulating cycle P1, but the drying phase of Laskar cycle LaN3.

Exposures further upstream and in Smithtown Creek on the Pennsylvania side of the Delaware River show that these units are part of the same type of cyclical sequence characteristic of the Lockatong and Passaic Formation. In the exposures at this stop, which is apparently close to the depocenter of the unit, the black unit is laminated to microlaminated. At exposures away from this area, fish-bearing oscillatory rippled black sandstones and siltstones become much more common. In addition, the black shales above and below the cycle exposed at this outcrop become much less prominent laterally, rapidly becoming purple.

The importance of this outcrop is that it shows that the basin was still deep and not filled with sediment; the generally shallow lake environments were a function of a lack of water to fill the basin, not a lack of space to hold the water. This could be due to either a long term drying trend or to a increase in the available surface area over which the water was spread. Because so many rift sequence show a shallowing upward of lake environments it seems more likely that a simple tectonic explanation is likely (e.g. basin filing model of Schlische and Olsen, 1990.

Correlation to the Titusville no. 1 core of the Newark Basin coring project is again unambiguous (Figure 51). The single cycle of the Warford Member seen at this stop seems unusually thick, and indeed it is here and in core. In fact, member C and the Warford Member represent the base of an interval of TS III in which the accumulation rate jumps upward and stays high until the top of the Neshanic Member (Figure 5). This may mark a regional pulse of extension within the large pulse giving rise to TS III, in general. It is probably not an accident that this time also marks the base of TS III in a number of basins, minimally the Culpeper and Argana basins.

Stop 2.4. Member L-M and Perkasie Member of the Passaic Fm. Pebble Bluff, Milford, NJ.

Latitude and Longitude: (aprox.) 40°34.60’N, 75°08.27’W

Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Passaic Formation
Age: Norian; ~215 Ma
Main Points:

1. Passaic Formation near border fault
2. Milankovitch cyclicity extending into conglomeratic facies
3. Comparision to central basin facies
4. Fossiliferous outcrops
5. Reptile footprint faunules

These outcrops, also described by Van Houten (1969, 1980), Arguden and Rodolpho (1987) and Olsen et al., 1989) are less than 2.4 km to the southeast from the border fault and consist of thick sequences (>20 m) of red conglomerate and sandstones alternating with cyclical black, gray, and red mudstone and sandstone. Dips average 10-15° NW, and there several faults, downthrowing to the east, between the largest outcrops. The thickest gray beds (see Figures 52, 53) are the Perkasie Member, making a McLaughlin cycle within the wetter part of long modulating cycle P2 and the wetter part Laskar cycle LaN4.

The Perkasie Member consists of Van Houten cycles and compound cycles showing the same pattern as the Lockatong (Olsen, 1986; Olsen and Baird, 1986). It consists of two sequential 100 ky) year cycles, each containing two well developed Van Houten cycles and weakly developed red and purple Van Houten cycle, succeeded upwards by red clastics (Figure 53). McLaughlin named the lower set of gray beds member N and the upper member O, which I have renamed short modulating cycle N and O, respectively. Underlying strata at these outcrops comprise the drier parts of member L-M, and these are largly conglomeritic at this site.

Conglomerates at Pebble Bluffs occur in three basic styles. 1) Poorly-bedded boulder-cobble conglomerate with pebbly sandstone interbeds. Matrix rich conglomerates are in places matrix-supported. These appear to define lenses that are convex-upward and bounded by the largest clasts at their edges and tops. These lenses appear to be debris flow lobes, in which some of the matrix may have been partially washed out by rain during periods of non-deposition. If correctly identified, the flow lenses are typically less than 30 cm thick and less than 5 m wide, similar to debris flows formed on mid to lower portions of steep fans. Pebbly sandstone and muddy sandstone include "trains" of isolated cobbles often oriented vertically. These cobble trains represent thin, low viscosity debris flows that are stripped of their matrix by shallow flash-flood streams. The sandstones appear to be broad, shallow stream deposits that may include hyperconcentrated flow as indicated by flat layering defined by the orientation of granules. At this locality, this style of conlomerte occurs in the upper part of member L-M.

2) Well-defined lenticular beds of pebble-cobble conglomerate separated by pebbly muddy sandstones with abundant root structures. The conglomerate beds are channel-form with abundant imbrication. Some internal coarsening and fining sequences are consistent with longitudinal bars (Bluck, 1982). Finer grained deposits resemble less-incised channels and overbank deposits. There are some hints of thin debris flow sheets. Abundant root structures filled with nodular carbonate suggest soil caliche. Again these types of

conglomerates are here almost entirely within member L-M although some occur in the gay parts of the Perkasie Member.

3) Grain-supported cobble-pebble conglomerate with sandy matrix. Granules and coarse sand show high degree of sorting suggesting wave reworking of finer fractions (LeTourneau and Smoot, 1985; Smoot and LeTourneau, 1989). These are associated with gray and black shales and oscillatory-rippled sandstones in Van Houten cycles. No unequivocal bar-form structures or imbricate ridges have been observed. These types are here restricted to the gray parts the Perkasie Member.

Laterally-continuous black and gray siltstones and claystones within division 2 of Van Houten cycles contain pinch-and-swell laminae, abundant burrows, and rare conchostracans. These are definitely lacustrine deposits, almost certainly marginal to the finer-grained facies more centrally located in the basin. These lacustrine sequences mark transgressions of perennial lakes over the toes of alluvial fans, much as LeTourneau and Smoot (1985) and LeTourneau (1985a) described in marginal facies of the Portland Formation in the Hartford basin of Connecticut. Division 2 of cycles comprising the Perkasie Member were produced by lakes which were almost certainly shallower than those which produced the microlaminated, whole fish- and reptile-bearing units in other parts of the Newark basin section. They evidently were deep enough, however, to transgress over at least the relief caused by the toes of alluvial fans. To what degree have more subtle transgressions of shallower lakes modified clastic fabrics elsewhere in this section?

The restriction of the conglomerate facies to the vicinity of the border fault and the association of debris flow and shallow stream deposits is consistent with an alluvial fan model (i.e., Nilson, 1982). Channel-form conglomerates suggest flash-flooding streams that are still consistent alluvial fans; but the abundance of interbedded fine sandstone suggest lower slopes than for the debris flow deposits. All of the deposits resemble distal low-slope fans or in the case of the coarse debris flow conglomerates, more distal parts of steep fans. Intercalation of lacustrine shales would appear to demand low slops. Coarsening up sequences of wave-formed deposits suggest intermittent introduction of material in receding lakes. This is probably a climatic as opposed to tectonic response because the shallowing is recognized basin-wide. Therefore, even the coarsest deposits accumulated on relatively low slopes. The requirement of low slopes means the present basin fault does not necessarily mark the apex and more likely the fans extended several miles beyond the present basin boundary (Smoot. 1991). The fans could have extended away from the present basin as thin veneers on pediment surfaces on basement, with fan material being continuously recycled basinward. This is consistent with the observations of a number of workers (Van Houten, pers. comm.; Manspeizer, pers. comm.) who noted that many of the clasts in the debris flow and poorly-sorted stream deposits are relatively well- rounded and mixed with highly-angular clasts.

Individual Van Houten cycles of the Perkasie Member in this area average 7 m thick, as compared with a mean of 6.5 m for the same cycles at the Bucks County Crushed Stone Quarry. The thickness of the ~100 ky cycles increase as well from 20.3 m at Ottsville to 28.1 m in this area (Figure 53). At New Brunswick, New Jersey, near the east side of the basin, the cycles are a mean of 4.4 m. This thickening towards the border fault is typical of most of the Newark Supergroup and dramatically illustrates the asymmetrical character of the half-graben. The trend to greater fossil richness is evident at this outcrop as is typical for more marginal facies of the Passaic Formation. The conchostracans present in the upper parts of division 2 in the upper black shale cycle in the second short modulating cycle of the Perkasie are absent in the more basinward exposures.

As we will see tomorrow at Stop 3.1, the central basin facies of the Perkasie Member is remarkably devoid of fossils. However at localities such as these, closer to the border fault, fossils of many kinds are actually quite common. This I believe to be due to two factors: 1) desiccation patterns; and 2) variability of accumulation rate. In the central facies of the Newark basin the Passaic (and Lockatong) are profoundly mud dominated. On the flat playas during dry phases of Van Houten cycles, the high frequency of wetting and drying events produce a desiccation breccia fabric that destroys most trace and aquatic fossils. Second, and probably more importantly, the accumulation rate in the center of the Newark basin was probably extremely even with a precompaction rate of only 1 mm or so a year. Such evenness of accumulation means that remains of plants or animals are not buried quickly enough to remove them from the high recycling rate part of the terrestrial ecosystem. In contrast, closer to the border fault, accumulation rates were much more erratic both vertically and horizontally. This is evident from the scale of individual deposition events, which is both on average larger and more erratic near the border fault than at the center of the basin. Hence, there is a much higher potential for swift burial and escape from ecosystem recycling.

At this particular outcrop, complete fossil specimens are rare but nearby outcrops have produced a wealth of material. The nearby abandoned Smith Clark quarry is such an example. The Smith Clark Quarry was in operation in the late l9th to 20th century and was developed to quarry flagstones from exposures of the short modulating cycle O of the Perkasie Member (Drake et al., 1961) of the Passaic Formation at Milford, NJ (Figure 53). The gray footprint-producing horizons in the Smith Clark Quarry have produced the types and much associated material of *Atreipus milfordensis*, *A. sulcatus* (Baird, 1957; Olsen and Baird, 1986), *Brachychirotherium parvum* (C. H. Hitchcock, 1889), *B. eyermani* (Baird, 1957), *Apatopus lineatus* (Bock, 1952a), and *Rhynchosauroides hyperbates* (Baird, 1957), as well as examples of *Grallator parallelus* (Baird, 1957), *Rhynchosauroides brunswickii* (Baird, 1957), "*Coelurosaurichnus* sp." (Olsen and Baird, 1986), and an uncertain tridactyl form (Baird, 1957) (Figure 54, 9). Associated gray sandstones have produced an important megafossil plant assemblage (Newberry, 1888; Bock, 1969) including *Glyptolepis playsperma* and *G. keuperiana* (Cornet, 1977), *G. delawarensis* (Bock, 1969), *Pagiophyllum* spp., (?) *Cheirolepis munsteri*, *Clathropteris* sp., and *Equisetites* spp. The interesting, unique specimen of the plant fossil *Ginkgoites miliordensis* Bock, 1952b (ANSP uncatalogued), from the Smith Clark quarry, was destroyed on loan in 1974 (Spamer, 1988), so comparisons cannot now be satisfactorily made regarding its relationship to other fossil plants.

At a nearby outcrop along Mill Road on the north side of Hackihokake Creek to the northeast, purplish and red footprint bearing beds of the Van Houten cycle overlying the gray beds of short modulating cycle O have produced *A. millordensis*, the type of *Chirotherium lulli* (Bock, 1952a; Baird, 1954), cf. "*Coelurosaurichnus* sp." (a different form than previously mentioned), and numerous small *Grallator* (PU 19910). Nearby exposures have also yielded clam shrimp in short modulating cycle O.

What is important about this particular assemblage, is it is on the whole, very similar to the assemblage from near Stop 1.3 which is about 3 m.y. younger and an assemblage from the lower Lockatong about 7 m.y. older (Olsen and Flynn, 1989), demonstrating very slow rates of faunal change through the Late Triassic, as well as no apparent effect of the Carnian-Norian boundary.

As mapped by Ratcliffe et al. (1986) on the basis of surface geology, drill cores, and a Vibroseis profile, the border fault in this area is a reactivated imbricate thrust fault zone dipping 32°SE. Core and field data reveal Paleozoic mylonitic fabrics of ductile thrust faults in Precambrian gneiss and early Paleozoic dolostone overprinted by brittle cataclastic zones of Mesozoic normal faults which form the border fault system of this part of the Newark basin.

Stop 2.5. Metlars Member of the Passaic Formation, Pottstown, PA.

Latitude and Longitude: (aprox.) 40°15.88'N, 75°39.73'W
Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Passaic Formation
Age: Norian; ~212 Ma
Main Points:

1. Cyclic Passaic Formation in Jacksonwald Syncline
2. Comparison to central basin facies
3. Stromatolites in transgressive portions of cycle
4. Comparison with core

A cut along abandoned railroad tracks exposes the upper part of the Livingston Member and the lower part of the succeeding Metlars Member. We will concentrate here on the lower Metlars Member.

The cyclicity we have seen in the lower Passaic Formation continues basically unabated up into middle and lower part of the upper Passaic. Here we can see the most prominent Van Houten cycles in the Metlars Member. This locality is especially interesting because of the stromatolites that are present in the transgressive portions of the lower of these two cycles (Figure 55). Evidently, as the climate became more humid, from the previous 20 ky cycle, the previously breccia-cracked mud flat became relatively well vegetated. This vegetation was then drowned by the expanding lake. Stromatolites encrusted the trunks and exposed roots of the drowned vegetation until the stromatolites themselves passed below the photic zone or were buried by accumulating muds. The lake then began to shallow with the deposition of abundant oscillatory rippled siltstones, followed by gray siltstones and fine sandstones with abundant desiccation cracks.

Stop 2.6. Road cut of upper Passaic Formation, Birdsboro, PA.

Latitude and Longitude: (aprox.) 40°16.68'N, 75°47.32'W
Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Passaic Formation

Age: Rhaetian; 206.5 Ma
Main Points:

1. Muted cyclicity in upper Passaic Formation in Jacksonwald Syncline
2. Lateral correlation of subtle cycles over very long distances
3. Just below last appearance of *Atreipus*

A road cut on the west-bound side of US Route 422 exposes the lower half of member JJ (Figure 56) in the upper Passaic Formation. Between the Ukrainian and Pine Ridge member of the Passaic Formation, the cyclicity of the Pasaaic Formation becomes very muted, although this less so in the Jacksonwald syncline than elsewhere. This muted cyclicity is typical of the Newarkian Rhaetian.

These outcrops display an example of the cyclicity typical in this interval. There is a large amount of oscillatory rippled siltstone and rooted mudstone. Van Houten cycles are marked usual by the presence of a distinct rooted and burrowed division 1, often calcareous, followed by a platy red mudstone of division 2. Division 3 often consists of platy mudcracked mudstones and oscillatory rippled siltstone and sandstone. In this case one of the more prominent cycles has a very distinctive division 1 consisting of a white calcareous mudstone with red mudstone *Scoyenia* burrows.

Immediately to the south west of these outcrops are excavations in these same units for Pioneer Crossing land fill and soon to be office park. These outcrops have produced a large number of excellent reptile footprints (Figure 57) in the upper Ukrainian Member and members II and JJ. Correlation of the Van Houten cycles (and larger cycles) with those seen in the Newark basin coring project cores has been tested and corroborated by the paleomagnetic stratigraphy of the Pioneer Crossing excavations. The distinctively colored, burrowed base of the Van Houten cycle in these outcrops is easily recognized within the Pioneer Crossing site and within Newark polarity zone E20n, where E20r.1r was also identified (Figure 56). A remarkable aspect of the Newark basin sedimentary succession is that unremarkable lacustrine lake maxima can be recognized in core an outcrop over distances in excesses of 150 km. This is important because it show that the cyclicity observed in the Newark basin coring project cores, even when quite subtle is reflecting basin wide changes, as well as providing a high resolution stratigraphic and temporal framework.

Atreipus is the most abundant dinosaurian track at levels below the Pioneer Crossing site, which is its highest definitive occurrence. Only small grallatorids have been found here. Above this level, grallatorids are the only dinosaurian tracks known from the entire Newark Supergroup.

Stop 2.7. Triassic-Jurassic boundary, Exeter Township, PA.

Latitude and Longitude: 40°18.76’N, 75°50.55’W
Tectonostratigraphic Sequence: TS III-IV
Stratigraphic Unit: Passaic Formation
Age: Rhaetian and Hettangian; 202 Ma
Main Points:

1. Exposure of Triassic-Jurassic boundary with Ir anomaly and fern spike

2. Last Triassic palynofloras
3. Last appearance of Triassic-type footprint assemblage.
4. Bone-bearing strata below boundary
5. Comparison to possible boundary sections in Hartford basin

In 1977, Cornet described a poorly exposed section present in the bed of a farm road in Exeter Township, Pennsylvania on the south limb of the Jacksonwald syncline, stratigraphically below the Orange Mountain Basalt (locally called the Jacksonwald basalt) (Figure [58]). The 78 m of largely shale exposure of the uppermost Passaic Formation produced three palynologically productive levels that he termed localities JB2, JB3, and JB6 (from the button up). According to Cornet (1977), JB2, JB3, JB4 produced typical (for the Newark) Rhaetian assemblages dominated by non-striate bisaccates, and circumsaccate (largely *Patinasporites densus*), with subordinate numbers of monosulcate and *Corollina torosus*. (although JB4 was very poorly preserved). The palynoflorule from JB6, on the other hand, was almost entirely (99%) *Corollina meyeriania* (Cornet, 1977), and Triassic forms were totally absent. Assemblages similar to JB6 characterize all younger Newark (and Hartford) basin sections. On the basis of this transition and comparison to European sections, Cornet concluded that the Triassic-Jurassic boundary lay between JB4 and JB6, and that it occurred in a "geological instant". From the late 1980s to the present, suburban development of the south limb of the Jacksonwald had begun with numerous mostly temporary exposures being produced with each foundation excavation. As it has turns out, the cyclicity and paleontological richness of the latest Triassic age sections here are better developed than anywhere else in the Newark basin, and the exposures in the Jacksonwald syncline provide the most detailed continental record of the Triassic-Jurassic boundary known. The following discussion is modified from Olsen et al. (2002c).

The boundary section exhibits strongly cyclical sediment variation with well-developed gray and black shales occurring periodically (in terms of thickness) in the Milankovitch pattern typical of Newark basin lacustrine sequences. In general, gray strata produce pollen and spores and thus the boundary section is better constrained biostratigraphically here than elsewhere (e.g., northern Newark basin). Over the years boundary sections have been exposed over a distance of about 2 km along strike with the easternmost (i.e., most basinward) exposures being the finest grained and having the highest proportion of gray strata. All of the Newark basin boundary sections are characterized by a litho- and biostratigraphy that is laterally consistent, despite the lateral changes in facies and accumulation rate (Figure 11).

A very prominent gray shale occurs about 25-30 m below the Orange Mountain Basalt (Figures 11, 59). This unit contains palynoflorules that are dominated (60%) by *Patinasporites densus* with variable amounts (5-20%) of *Corollina torosus*, and other pollen and spores (Cornet's JB4). This is typical of many older Late Triassic palynoflora assemblages from the Jacksonwald syncline. Above this gray shale are variegated red and gray shales and sandstones that have a lower abundance (5-40%) of *Patinasporites densus*. Approximately 8-12 m below the Orange Mountain Basalt another prominent marker bed occurs: a brown to "blue-gray sandstone" with abundant comminuted charcoal and wood, which is referred to as the "blue-gray sandstone" bed (Figure 11). This unit generally lies directly above a thin (1-10 cm) coal bed or carbonaceous shale. The highest stratigraphic occurrence of *Patinasporites densus* occurs about one meter below the sandstone.

This palynoflorule (sample 6-2 of Fowell, 1994) is dominated by *Corollina* (73%) with about 10% *Patinasporites*. This is the highest assemblage having a Triassic-aspect palynomorph assemblage.

In the 40 cm below the "blue-gray sandstone", palynomorph assemblages are consistently dominated by trilete spores belonging to taxa usually attributed to ferns (as first discovered by Litwin in Smith et al., 1988), the dominant species being *Granulatisporites infirmus* (Fowell, pers. comm., 2002). Within a couple of centimeters of the base of the "blue-gray sandstone", the proportion of spores reaches a maximum of 80% (Fowell et al., 1994). *Patinasporites densus* is absent from these assemblages, and these assemblages are considered to be of earliest Jurassic age. Such fern-dominated assemblages are unknown elsewhere in Newark basin strata of Triassic age, although we will visit a similar occurrence on Day 4 (Stop 4.2). Fowell refer to this very anomalous high proportion of fern spores as a "fern spike", in parallel with the terminology used for the Cretaceous-Tertiary boundary (e.g., Tschudy et al., 1984; Nichols and Fleming, 1990). It is within this fern spore-rich interval that the iridium anomaly occurs (see below). Above the "blue-gray sandstone", palynoflorules are dominated by *Corollina* whilst *Patinasporites* and other Triassic-type taxa are absent (e.g. Cornet's JB6). The character of these assemblages is similar to that of the Jurassic strata overlying the basalts throughout the Newark Supergroup, and we consider them to indicate a Jurassic age for the uppermost Passaic Formation. Thus, again in analogy to the Cretaceous-Tertiary boundary, we hypothesize that the fern spike at least approximates the base of the Jurassic, and hence the Triassic-Jurassic boundary (Figure 11). Based on the cyclostratigraphically-based accumulation rate, the last Triassic aspect palynoflorule occurs, conservatively, within 25 ky of the base of the Orange Mountain Basalt, the interval of time between this Triassic assemblage and the lowest definitive Jurassic assemblage (Jb-6 of Cornet, 1977) is less than 10 ky. Similarly, the Triassic-Jurassic boundary, as defined here by the fern spike, occurs within 20 ky of the base of the Orange Mountain Basalt.

Spurred on by the biological and physical similarity between these sections and the western US K-T boundary (Figure 60), Olsen et al. (2002b, 2002c) examined iridium and other elemental concentrations at four sections along strike in this area directly around the fern spike (Sections I-III and Grist Mills: Figure 61). Section I and II comprise the exposure we will visit. The samples show variations in Ir content from 19 to 285 ppt (Olsen et al., 2002b). All other sections except Section I show a distinct Ir anomaly directly at the boundary with a distinct systematic association between Ir content and stratigraphy. The elevated levels of Ir are mostly associated with the higher levels of Al in a the white smectitic claystone described by Smith et al. (1988), directly beneath the thin coaly layer (Figure 60). It is possible the relatively weak Ir anomaly seen thus far is a consequence of dilution by the rather coarse sampling level (ca. 3 cm / per sample) required by the very high accumulation rates (ca. 1 m / 2000 yr) in the sampled part of the Newark basin. We can probably rule out a simple diagenetic concentration of Ir along a redox boundary, because of the good correlation between Ir and stratigraphy, in the face of a lateral facies change from gray and black strata in the east to virtually entirely red strata in the westernmost section (Grist Mills). Indeed, the sample with the highest Ir content at the Grist Mills section is red (177 ppt. sample TJ 28). In the one section (I) that did not show a systematic association between Ir content and stratigraphy, Ir levels were highest in the "blue-gray sandstone" rather than in the spore-rich clays just below it. This could be because our sample of the sandstone (sample TJ 1) contained mud chips eroded from an Ir enriched layer upstream. The sandstone was bulk processed and it will be necessary to run separate analyses on sandstone and clay pebble separates to test this hypothesis.

The situation is does, unfortunately, not become any clearer when considering the contents of other elements. Apart from Ir by coincidence spectrometry, we have determined the abundances of a total of 44 major and trace elements in all samples. The results are reported in Olsen et al. (2002c). Comparing the trends of the Ir data with those of other siderophile elements, such as Co and Ni (also Cr), which are often used as tracers of meteoritic components, does not yield a distinct correlation. For example, in section I, the highest Ni and Co abundances are at samples TJ-2 and TJ-3, whereas Ir shows more variation in the section. No correlation is apparent for samples of section II and the variations in section III do not appear to be significant. On the other hand, in section IV, those samples with the highest Ir contents (TJ-28 – 30) do not have Cr, Co, and Ni abundances that are as significantly and notably elevated as the Ir contents. However, the Ni content does show an increase from about 20 ppm to about 50 ppm, which is broader than the Ir peak, and is centered at the same part of the section. The values for Co show more variation, but follow the same trend as for Ir and Ni.

The trace element data also do not support the idea that the Ir enrichments could be related to volcanic ash. Elements that include Cs or Al, but also Cu and V, could be typical of (altered) volcanic components. Examination of the values for these elements (Table Y) and comparison with the Ir data do not reveal any significant correlations. The variations in section I are irregular. In section IV, the contents of, for example, Cs are varying with no correlation to the distinct Ir enrichment and the (associated and noticeable) Co and Ni abundance peak. The highest Cs abundances occur for samples outside of the zone of siderophile element enrichment. Thus, we cautiously assign a low probability to a volcanic interpretation of the Ir enrichments.

A significant problem with our analysis of the association between Ir abundance and the fern spike in the Jacksonwald syncline sections is that the geochemical and palynological analyses were not conducted on the same samples, or even at the same sections, and there is considerable variability from section to section in both variables. In an attempt to mitigate this problem and facilitate comparison of the Ir and pollen and spore data, we have averaged the Ir data and combined the spore data from all of the Jacksonwald synclines sections examined to date, using the base of the blue-gray sandstone as the correlative datum (Figures 11, 61). No attempt has been made to account for possible lateral changes in accumulation rate.

The averaged and combined data show a strong correlation between spore percentage and Ir content. However the spore maximum is below the Ir maximum and the spore "spike" appears quite broad. This could reflect an actual offset between the two data sets, or it could reflect small variations in accumulation rate or depth of erosion of the overlying blue-gray sandstone at different sections. Existing data do not permit these hypotheses to be tested. Clearly, what is needed is very detailed sampling of section on which spits of the same samples are subjected to palynological and geochemical analyses. In addition, Ir measurements are clearly needed from a broader stratigraphic swath around the boundary to assess background Ir levels. The available data are, however, are very encouraging and do suggest that there is a modest Ir anomaly at the biologically identified boundary and that it is associated with a K-T-like fern spike.

Reptile footprint taxa broadly follow the same pattern as the palynological stratigraphy. Footprint faunules have been recovered at many levels within the Jacksonwald syncline and there is a concentration of productive levels near the palynologically-identified Triassic-Jurassic boundary (Silvestri and Szajna, 1993; Szajna and Silvestri, 1996; Szajna and Hartline, 2001; Olsen et al., 2002b) (Figure 62). Assemblages in rocks of Triassic age contain abundant *Brachychirotherium* (suchian) and more rare *Apatopus* (phytosaur), a form informally designated "new taxon A" of Szajna and Silvestri (1996) (suchian), as well as *Rhynchosauroides* (lepidosauromorph), *Batrachopus*, (crocodylomorph suchian) a form referred to "new taxon B" (Szajna and Silvestri, 1996) (suchian), and abundant small- to medium-sized dinosaurian tracks usually referred to as various species of *Grallator* and *Anchisauripus* (i.e., *Eubrontes* spp. in the terminology of Olsen et al, 2002b). *Brachychirotherium*, *Apatopus*, and "new taxon B" have never been found in strata of Jurassic age anywhere, despite the global abundance of Early Jurassic age footprint assemblages. The highest footprint assemblage with *Brachychirotherium* and "new taxon B" occurs about 11 m below the "blue-gray sandstone" and the fern spike (Fig. 5). Even closer to the boundary is a poorly sampled footprint-bearing level with *Rhynchosauroides*, *Batrachopus*, and *Grallator* and *Anchisauripus* (*Eubrontes* spp.) that is about 7 m below the "blue-gray sandstone" and fern spike. Although thus far not very productive, only *Grallator* and *Anchisauripus* (*Eubrontes* spp.) have been found above the "blue-gray sandstone" in the Jacksonwald syncline.

Abundant tetrapod bones occur in a zone about 400 m below the Orange Mountain Basalt in the Jacksonwald syncline in member TT. Thus far, this interval has produced numerous skeletal remains, including skulls and articulated skeletons of the procolophonid parareptile *Hypsognathus fenneri*, and the crocodylomorph cf. *Protosuchus*, as well as other as yet unidentified remains, including probable phytosaur teeth. These bone occurrences are about 800 ky older than the Triassic-Jurassic boundary, and help constrain the ranges of Triassic-type taxa. Presumably these bone producing levels are within TS III. There is no evidence here, however of a tectonostratigraphic sequence boundary here.

Correlation of the Jacksonwald syncline sections with the Newark basin cores is fairly straightforward, despite the muted cyclicity in the uppermost Passaic Formation in the cores. A thin but well-defined interval of reversed polarity (E23r) occurs about 17 m below the Orange Mountain Basalt in the Martinsville no. 1 core (Kent et al., 1995; Kent and Olsen, 1999a). This reversed interval is sandwiched between two very thick normal polarity intervals (E23n and E24n). Magnetic polarity chron E23r has also been identified in the Jacksonwald syncline section (Olsen et al., 1996a). The pattern of prominent gray beds in the Jacksonwald syncline sections and their relationship to chron E23r is matched very closely by the relationship between very thin gray and purple bands and chron E23r in the Martinsville no. 1 core. This laterally repeated pattern permits precise outcrop and core correlation (Figure 59) (Olsen et al., 1996a), in particular tying the Jacksonwald sections to the stratigraphy in the northern Newark basin where the cyclostratigraphy of the bulk of the Jurassic section has been established by study of the ACE cores (Olsen et al., 1996b).

Exposures in quarries and at construction sites in the vicinity of Paterson and Clifton, New Jersey, in the same areas in which the ACE cores were drilled, have produced a series of important fossil assemblages within the upper Passaic Formation. Although a magnetic stratigraphy does not exist for this area of the Newark basin section, the pattern of purple intervals in the ACE cores matches that seen in the Martinsville no. 1 core, allowing lithostratigraphic correlation. Based on this correlation, the Martinsville no. 1 core and the ACE cores appear to have nearly the same accumulation rate for the uppermost Passaic Formation.

The uppermost few meters of the Passaic have produced an enormous number of footprints from a variety of exposures (Figures 59, 63). These footprint assemblages contain only *Rhynchosauroides*, *Batrachopus*, and small to large *Grallator*, *Anchisauripus*, and *Eubrontes* (*Eubrontes* spp.). Critically, these assemblages contain the oldest examples of *Eubrontes giganteus*, a dinosaurian track about 20% larger than any older ichnospecies (Olsen et al., 2002b). At one locality within the footprint-bearing sequence, a gray lens of sandstone and shale has produced a macroflora dominated by the conifers *Brachyphyllum* and *Pagiophyllum*, and the fern *Clathropteris meniscoides*, as well as a poorly preserved palynoflorule dominated by *Corollina* and lacking Triassic-type taxa. This footprint and plant assemblage is thus of earliest Jurassic age, an interpretation supported by its stratigraphic position compared to the Martinsville no. 1 core (Figure 59).

In close proximity to these footprint and plant localities are the exposures that yielded skeletal remains of *Hypsognathus fenneri*, including the holotype specimen (Sues et al., 2000). These occurrences are about 45 m below the Orange Mountain Basalt. Based on correlation with the Martinsville no. 1 core and the Jacksonwald syncline sections, these represent the youngest examples of typical Triassic osteological taxa in eastern North America. Based on the cyclostratigraphy, the *Hypsognathus*-bearing horizons are within 200 ky of the palynologically defined Triassic-Jurassic boundary.

DAY 3. CENTRAL NEWARK BASIN AND CORES

Stop 3.1. Member L-M and Perkasie Member, New Brunswick, NJ

Latitude and Longitude: (aprox.) 40°29.27’N, 74°26.10’W
Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: Passaic Formation
Age: Norian; 215 Ma
Main Points:

6. Central basin facies of Perkasie Member
7. Lack of fossils
8. Comparison with core.

The Perkasie Member and underlying member L-M of the Passaic Formation are exposed along a road cut and contiguous quarry in New Brunswick, New Jersey (Figure 53). The section consist of about 100 m of continuous exposure, overlapping nearly entirely the section we saw at Stop 2.4, yesterday.

In contrast to the outcrops at Stop 2.4, virtually the entire section here is dominated by mud, mostly massive with a desiccation breccia fabric, no definitive fossils (apart from rizoliths - roots) have been found. We will spend only a short time here, enough to be a bit familiar with the section which we will later see in core (see below).

Stop 3.2. Newark basin cores, Busch Campus, Rutgers University, Piscataway, NJ

Main Points:

1. Examples of core from all the major units we have seen
2. Includes Triassic-Jurassic boundary in two facies
3. Difference in appearance between outcrop and core
4. Lateral and vertical continuity
5. Cyclicity and time scale

Both the cores of the Newark Basin Coring Project (NBCP) and the Army Corps of Engineers (ACE) Passaic River Project are housed at Rutgers University. Here we shall examine core from the levels we have seen over the last few days, including the Triassic-Jurassic boundary, except the Stockton Formation, which requires too much core to be displayed to be meaningful.

3.2.a: Lockatong Formation, Skunk Hollow Member (NBCP, Nursery no. 1) (Figure 49)

Main Points:

1. Same cycles as seen at Stop 2.2
2. Very well behaved Milankovitch cyclicity
3. Very little lateral change in facies over 25 km
4. Thickening towards border fault

3.2.b: Passaic Formation, Perkasie Mb. (NBCP, Titusville no. 2 and Rutgers no. 1) (Figure 64)

Main Points:

1. Lateral change in facies from Stop 2.4 from edge to middle of basin
2. Thickening and increase in cyclicity detail from Rutgers to Titusville core sites
3. Almost no difference between exposure at Stop 3.1 and Rutgers core site
4. Difference in appearance between outcrop and core
5. Lateral and vertical continuity

3.2.d: Passaic Formation, Metlars Member (NBCP, Rutgers no. 2 and Somerset no. 1) (Figure 65)

Main Point:

1. Lateral changes in facies from Rutgers to Somerset coring sites and Stop 2.5

3.2.e: Passaic Formation, Exeter Member and Triassic-Jurassic boundary and basal Orange Mountain Basalt (NBCP, Martinsville no. 1) (Figure 59)

Main Points:

1. Triassic-Jurassic boundary in mostly red facies
2. Small polarity zone E23R
3. Boundary clay??
4. Contact with oldest CAMP flows

3.2.f: Passaic Formation, Exeter Member and Triassic-Jurassic boundary and basal Orange Mountain Basalt – sandstone facies (ACE, C-88, C-87)

Main Points:

1. Triassic-Jurassic boundary in red sandstone facies
2. Contact with oldest CAMP flows
3. Earliest, earliest Jurassic footprint levels and plant level

3.2.g: Orange Mountain Basalt and basal Feltville Fm. (NBCP, Martinsville no. 1) (Figure 59)

Main Points:

1. Distinctive cyclical sequence
2. Limestone-bearing cycles
3. Onlap of basal Feltville – compound TS II – TS IV contacts
4. Contact with CAMP flows

3.2.h: Orange Mountain Basalt and basal Feltville Formation (ACE, PT-26, C-92) (Figure 66)

Main Point:

1. Lateral change in facies and expansion of section from Martinsville no. 1
2. Comparison with basal Shuttle Meadow Formation of Hartford Basin (see Stop 3.3.b, below)

3.2.i: Towaco Formation (ACE, C-128)

Main Points:

1. Continuity of cyclical pattern up through Towaco Formation
3. Massive increase in accumulation rate
4. Similarity to Passaic and Lockatong cycles
5. Comparison with middle East Berlin Formation of Hartford Basin (see Stop 4.7, below)

3.2.j: Boonton Formation (NBCP, C-134)

Main Points:
1. Continuity of cyclical pattern up into Boonton Formation
2. Massive increase in accumulation rate
3. Similarity to Towaco cycles

Stop 3.3. Hartford basin cores, LDEO, Columbia University, Palisades, NY

Main Points:
1. Similarity and differences with Newark basin Triassic-Jurassic boundary
2. Comparison between cyclical sequences in Shuttle Meadow Formation and Feltville Formation

3.3.a: Hartford basin Triassic-Jurassic boundary (cores B-2, B-3)

Main Points:
1. Base of TS IV in the Hartford basin
2. Gray interval limited to upper 2 m of New Haven Formation
3. Locally contains at least earliest Jurassic flora (micro and macro)
4. Pillowed Talcott Basalt

3.3.b: Hartford basin: lower Shuttle Meadow Formation and Talcott Basalt (core B-1) (Figure 67)

Main Points:
1. Lacustrine cycles in lower Shuttle Meadow Formation
2. Limestone-bearing cycles
3. Comparison to lower Feltville Formation
4. Volacanoclastic member of Talcott Basalt

DAY 4. HARTFORD BASIN SECTION

Stop 4.1. Lower New Haven Formation, I 691, Cheshire, CT

Latitude and Longitude: (aprox.) 41°33.53'N, 72°54.47'W
Tectonostratigraphic Sequence: TS III
Stratigraphic Unit: New Haven Formation
Age: Norian; ~215 Ma
Main Points:
1. Basal formation of Hartford basin sequence
2. Entirely Fluvial-alluvial
3. ?Meandering river system
4. Well developed caliche profiles

5. Reptile bone-producing facies and locality
6. Radiometric age

This outcrop reveals about 130 m of New Haven Formation dipping about 10°E towards the boundary fault of the Hartford basin (Figure 68). The section begins about 650 m above the base of the 2-km-thick formation and consists entirely of deposits of meandering streams and rivers (McInerney and Hubert, 2002). The specific kinds of deposits seen here are characteristic of the lower part of the formation in much of the basin. The middle New Haven Formation is dominated by braided river deposits and the upper by meandering or anastomosing fluvial systems. The transition to TS 4 is marked by an appearance of a larger suite of lithologies including gray strata that may be of marginal lacustrine origin (see Stop 3.3a and Stop 4.8).

According to McInerney and Hubert (2002), this section consists of 22 fluvial cycles, each composed of cross-bedded white, gray and buff channel sandstone and gravel and overlying red massive muddy sandstone and mudstone of floodplain origin. Thicker beds of sandy mudstone commonly contain root casts, carbonate nodules, and tubules that form discrete layers. The carbonate layers are interpreted by Hubert et al. (1978) as caliche horizons formed on the flood plains. They believe that the caliche profiles are indicators of semi-arid conditions after Gile et al. (1966). They interpret these cycles as being produced by the migration of a meander belt towards and away from the outcrop area. In addition, they recognize four "megacycles" showing an upward increase in amount of time it takes to form the caliche profiles (Hubert et al., 1978). No single climatic type can be assigned to the caliches. Perhaps they formed during the drier phases of the longer climate cycles (100 ~400 ky cycles). The meter scale cycles at this outcrop, for the most part, cannot be traced across the highway and, because they are formed by the lateral migration of rivers and streams, there is no reason to believe they are cause by cyclical climate change. The megacycles of McInerney and Hubert (2002), however, might very well be caused by climate change, perhaps the 400 Ky cycle.

The New Haven Formation, quite unlike coeval coarse grained facies in the Culpeper, Gettysburg, and Newark basins, apparently does not grade laterally into lacustrine deposits, and paleocurrent data indicate through-flowing streams coming from the northeast across the basin. Thus, transgressive regressive lacustrine cycles are absent from the New Haven Arkose. Nonetheless, if periodic climate change was responsible for the Van Houten cycles in the contemporary strata from other adjacent basins, then those climate fluctuations must have influenced the Hartford basin as well. Because the duration of the climatic cycles may be similar to the amount of time it takes to form the caliche profiles (Hubert et al.,1978), no single climatic type can be assigned to the caliches and associated strata of the New Haven Arkose. The caliches may have formed only during the drier parts of the climatic cycles. While our ability to interpret climate change from fluvial sequences is just in its infancy, it should be possible to say something definitive about the average period of the megacycles and their climatic phasing by using paleomagnetic polarity stratigraphy to correlate this section with the Newark basin GPTS. Preliminary sampling does indicate both normal and reversed polarity and that a reversal stratigraphy will be obtainable from this exposure and this formation in general.

This outcrop gains special merit because it has produced a well preserved skull of a crocodile relative called *Erpetosuchus* (Olsen et al., 2000b) (Figure 69). *Erpetosuchus* is otherwise known from somewhat older strata in Scotland (also from an Atlantic marginal rift). The skull was found about 45 m above the base of the section. When found it looked very much like a bit of caliche. *Erpetosuchus* was a long legged, slender quadruped, and unlike modern crocodiles, it was fully terrestrial, and reached a total length of only about 60 cm. Direct U-Pb dating of soil caliche calcite from within 2 m of the skull average 213+6 Ma (Wang et al., 1998). This is direct evidence that this part of the New Haven Formation is Middle Norian in age, which is in agreement with other biostratigraphic data. However, the Scottish *Erpetosuchus* is of Carnian age (if correctly dated) and this occurrence thus extends the range of the former "singleton" family into another stage, further diminishing the supposed Carnian-Norian mass extinction (Olsen et al., 2000b).

Stop 4.2. "*Clathopteris* locality", Holyoke, MA

Latitude and Longitude: (aprox.) 42° 12.98' N, 72° 39.50' W
Tectonostratigraphic Sequence: TS IV
Stratigraphic Unit: Upper New Haven Fm. or lower Shuttle Meadow Fm.
Age: ?Rhaetian-Hettangian; ~202 Ma
Main Points:

1. Physical similarity to Triassic-Jurassic boundary in Newark basin
2. Major fern (*Clathropteris*) macrofossil locality
3. Very high spore counts – "fern spike"?
4. Fluvial or marginal lacustrine
5. Meaning for biostratonomy of fern spikes
6. Testing pattern

An isolated small set of exposures along Southampton Road in Holyoke, MA was discovered in the 1970s and has produced the best preserved examples of the dipteraceous fern *Clathropteris meniscoides* in the Newark Supergroup (Figure 70).

The outcrop, still only superficially studied, consists of (from the bottom up) a few meters of red and brown sandstone and mudstone, followed by ~5 meters of gray and tan and yellow-weathering pebbly sandstone and siltstone. These coarser units are draped by a few cm of gray rooted clay, covered by a mat of *Clathropteris* and *Equisetities* in growth position (albeit compressed). The *Clathropteris* mat is overlain by tan and yellow-weathering fine conglomerate, pebbly sandstone, and siltstone.

It is clear from surrounding outcrops that this exposure lies below the Holyoke Basalt and is within the upper New Haven Formation or lower Shuttle Meadow Formation, but in this part of the northern Hartford basin, the Talcott basalt is lacking. Lithologically, the sequence is clearly like that of the Shuttle Meadow, not typical New Haven Formation, but such lithologies begin in TS IV of the New Haven Formation (Stops 3.3a and 4.8). By convention this unit is mapped as Shuttle Meadow but the chronostratigraphic meaning of this is certainly not clear. Cornet (1977) gives an estimated position of this section as 148 m below the Holyoke basalt, however, the very irregular topography suggests to me the presence of a series of faults, making speculative any thickness estimate outside the existing exposure.

This section is thus lithologically similar to the Triassic-Jurassic boundary in the Jacksonwald syncline of the Newark basin we saw at Stop 2.7. There, however, no supporting evidence of the major palynological or reptile footprint turnover, because there are no stratigraphically adjacent palynological or footprint levels. Cornet (1977) did excavated large numbers of *Clathropteris* from this locality, and was able to recover examples of the spore *Granulatisporites infirmus* from sporangia of fertile pinnae of the fern (Cornet and Traverse, 1975). The mat itself and the underlying claystone comprises a "fern spike" dominated by *Granulatisporites infirmus*, *Converrucosisporites cameronii* (which morphologically grades into the latter), and *Corollina meyeriana* with subordinate amounts of *Dictyophyllidites paramuensteri*, *Dictyotriletes* sp., *Pilasporites allenii*, *Podocarpidites* sp., *Corollina torosus*, *Corollina murphyi*, *Corollina simplex*, *Circulina simplex*, *Cycadopites andrewsii*, and *Cycadopites* sp. (Cornet and Traverse, 1975). *Granulatisporites infirmus* is the dominant spore in the Newark basin fern spike as well, increasing the similarity. There are no other similar sequences know from the entire Hartford basin.

Two hypotheses present themselves for the similarity between this exposure and the Triassic-Jurassic boundary in the Newark basin: 1) both occurrence represent only distinctive habitat of *Clathropteris* and the fern spike at boundary section in the Newark basin is just a fortuitous occurrence of *Clathropteris* in a boundary transition; 2) the distinctive suite of lithologies and the fern spike represent the boundary phenomena.

It is worth noting that abundant *Clathropteris meniscoides* is not only typical of the Shuttle Meadow Formation, but all correlative strata in the Newark Supergroup of the United States, as well as the upper most Passaic Formation (e.g. boundary strata). In addition it is characteristic of the Rhaeto-Liassic in Greenland, and northern Europe, as well as China and parts of Southeast Asia. It is rare, however, in all other parts of the Newark Supergroup. At this point, data are insufficient to tell if *Clathropteris meniscoides* increases globally at the boundary.

Other data are clearly needed to tell if this section really is the Triassic Jurassic boundary. Most obvious, is that other pollen-bearing horizons are needed below and above the putative "fern spike" to see if it lay at the palynological extinction level. The identification of E23r would confirm correlation with the Newark basins boundary, and we have processed on sample that, while normal, does indicate well behaved magnetic behavior and a polarity stratigraphy thus should be obtainable. (D. V. Kent, pers. comm., 2002). Finally there should be an examination of the concentrations of PGEs and other elements. It may not be possible to carry out these investigations at this locality to the degree necessary without modest coring.

Stop 4.3. New Haven and Shuttle Meadow Fm. and Holyoke Basalt, Interstate Rt. 91, Northampton, MA

Latitude and Longitude: (aprox.) 42° 17.03' N, 72° 36.88' W
Tectonostratigraphic Sequence: TS IV

Stratigraphic Unit: Upper New Haven Fm., lower Shuttle Meadow Fm., Holyoke Basalt
Age: ?Rhaetian-Hettangian; ~202 Ma
Main Points:

1. Basal TS IV
2. Possible boundary section
3. Continuity of lower limestone sequence of Shuttle Meadow Formation
4. Fluvial to deep-water lacustrine environments
5. Holyoke Basalt

A large cut on the southwest side of the south bound lanes of Interstate 91 on the north side of Mount Tom exposes over 100 m of upper New Haven Formation and lower Shuttle Meadow Formation (Figure 71). The upper Shuttle Meadow Formation is not exposed in this cut, but the lower flow of the Holyoke Basalt is exposed. This section was described by Brophy et al. (1967) and in part by Cornet (1977), but has never been measured in detail.

The base of the section consists of a coarse conglomerate in excess of 15 meters thick, which is probably a basal conglomerate of TS IV. The upper New Haven tends to be finer grained and more distinctly red. This is followed by a 13 m thick sequence of predominately red sandstone and mudstone that lithologically marks the base of the Shuttle Meadow Formation, and which probably contains the Triassic-Jurassic boundary. The succeeding 3 m is a transgressive sequence (division 1) culminating in rooted gray silt and sandstone. Division 2 consists of about 2 m of platy dark gray laminated limestone and calcareous siltstone grading up into crudely laminated black siltstone. The platy laminated limestone contains limestone nodules with well-preserved examples of the fish *Semionotus*, *Redfieldius* and *Ptycholepis* (Cornet, 1977; Cornet and Traverse, 1975; Olsen et al, 1982) as well as abundant coprolites (coelacanth). This is certainly the lower limestone unit of the Shuttle Meadow Formation. A 4 m thick sequence of Gilbert-type delta forests of sandstone overlies the lower limestone and siltstone and tongues downward into it. A gray (2 m), then predominately red (16 m) clastic sequence follows, followed by a long expanse of no exposure until the splintery columns of the Holyoke Basalt are reached.

No one has yet to tried to search for the boundary in this section. If it is preserved as an event horizon, it is probably within the lower red clastic sequence, where perhaps on of the red or purplish clay rich layers might be prime suspects. Certainly, the magnetic stratigraphy of this section would prove interesting.

The Holyoke Basalt is an HFQ-type quartz normative basalt, essentially identical in chemistry to the lower two flows of the Preakness Basalt (Puffer et al., 1981). Interestingly the flow here exposed is also fractured like the lower flow of the Preakness. Prevot, M. and McWilliams (1989) have show that there is a magnetic excursion in the lower Preakness, Holyoke, and Deerfield basalt, virtually assuring their simultaneous eruption.

Stop 4.4. Rest stop on Interstate Rt. 91 in the Granby Tuff

Latitude and Longitude: (aprox.) 42°15.28' N, 72° 37.25' W
Tectonostratigraphic Sequence: TS IV

Stratigraphic Unit: Granby Tuff
Age: Hettangian; ~202 Ma
Main Points:

1. Volcanoclastic unit equivalent to Hampden Basalt
2. Mixture with sediments
3. Local feeder dikes, eruptive locus

Cuts at and adjacent to a rest stop on the southbound side of Interstate Rout 91 expose a few meters of the Granby Tuff. The Granby Tuff was named and described by Emerson (1891, 1917) and described by Balk (1957). It is a black to maroon compact or stratified basaltic tuff or tuffaceous sandstone. It locally includes basaltic breccia and is intruded by dikes and sills of Blackrock diabase and "Mount Tom plug" (probably the equivalents of the Bridgeport dike. It overlies or is interbedded with flows of the Hampden basalt. It appears fairly clear that this was an area of fissure eruption for the Hampden basalt (Foose et al., 1968). There are no modern studies on this tuff, but is clear that much of it is water reworked.

Stop 4.5. Holyoke Footprint Preserve, Holyoke, MA.

Latitude and Longitude: (aprox.) 42°15.40' N, 72° 36.92' W
Tectonostratigraphic Sequence: TS IV
Stratigraphic Unit: Portland Formation
Age: Hettangian; ~201.5 Ma
Main Points:

1. Basal Portland Formation
2. Cyclical sequences nearly identical to basal Boonton Formation of Newark basin
3. Location for type specimen of *Eubrontes giganteus*
4. Evidence for herding in theropod dinosaurs
5. Rarity of herbivore tracks

A natural outcrop on the dip slope of the Hampden Basalt and Granby Tuff along the Connecticut River reveals about 30 m of basal Portland Formation (Figure 72). These outcrops contain large numbers of dinosaur footprints, notably *Grallator*, *Anchisauripus* and *Eubrontes* (Figure 73). The flaggy siltstones low in the section were quarried for flag and building stones in the 19^{th} century and in 1836 Edward Hitchcock named *Eubrontes* (*Ornithichnites*) *giganteus*, the first dinosaur footprint described (Figure 74). It is this ichnotaxon, of course, that makes its first appearance just above the Triassic-Jurassic boundary. The width and spacing of tracks suggests that the track maker of *Eubrontes* was more than 2 meters tall at the hip and 6 meters long, but no osseous remains assignable to this animal have been recovered from the Hartford basin. The skeletal remains of the theropod dinosaur *Dilophosaurus*, known from the Early Jurassic Kayenta Formation of Arizona, are the best match for *Eubrontes*.

Ostrom (1972) mapped out the distribution of mostly *Eubrontes* tracks on the main slab, nearest the retaining wall for Rt. 5. The trackways display a marked preferred orientation, within 30° of west (Figure 73. Ostrom concluded that this and other tracksites strongly indicated that at least some dinosaurs traveled in herds. It is also possible, however, that they were walking parallel to transient paleo-shorelines.

As we have seen from the Newark basin Jurassic, a remarkable aspect of these assemblages is the extraordinarily low diversity suggested by track sites such as these. In addition the tracks of herbivores, such as the ichnogenera *Anomoepus* (small ornithischian), and *Otozoum* (prosauropod) are reparably rare. This is typical, not only of the first few hundred thousand years of the Early Jurassic of eastern North America, but also of the earliest Jurassic globally.

The gray beds outcropping in the river match in position to those in the basal Portland of the Park River Cores (Figure 72) and as such they represent a wet phase of a short modulating cycle in the dry phase of a McLaughlin cycle, one that begins in the underlying East Berlin Formation.

Stop 4.6. Dinosaur State Park, Rock Hill, CT.

Latitude and Longitude: (aprox.) 41°39.03' N, 72°36.48' W
Tectonostratigraphic Sequence: TS IV
Stratigraphic Unit: East Berlin Formation
Age: Hettangian; ~201.5 Ma
Main Points:

1. Upper gray and black Van Houten cycle of East Berlin
2. Abundant dinosaur tracks (*Eubrontes*) in regressive portion of cycle
3. No evidence for herding in theropod dinosaurs
4. Rarity of herbivores

This site was discovered in 1966 during excavation for the foundation of a state building. Exposures here have revealed nearly 2000 reptile tracks, most of which have been buried for preservation and future exhibition (Figure 75). The present geodesic building at the park houses approximately 500 tracks (Figure 76). The tracks are found in the gray arkoses, siltstones, and mudstones of the East Berlin Formation, about 20 m below the contact with the Hampden Basalt. Ripple marks, raindrop impressions, mudcracks, and the footprints indicate shallow-water conditions and some subareal exposure. The track-bearing beds grade upward into gray mudstone and then red sandstone and mudstone. These strata are part of the uppermost gray cycle in the East Berlin Formation and they are clearly part of the regressive phase of that cycle.

The ichnogenera *Eubrontes*, *Anchisauripus*, *Grallator*, and *Batrachopus* have been identified at this locality (Ostrom and Quarrier, 1968). All but *Batrachopus* were made by small to large theropod (carnivorous) dinosaurs. *Batrachopus* was made by a small early, fully terrestrial protosuchian crocodilian. *Eubrontes giganteus* tracks are the most common and are the only tracks visible in situ within the geodesic dome. Because of the popularity of this site, *Eubrontes* is now the Connecticut state fossil. Based on what appear to be claw drags without any pad impressions, Coombs (1980) suggested that some of the track makers were swimming, but Farlow and Galton (2002) argue that the same kind tracks were made by the *Eubrontes* trackmaker walking on a hard substrate. This is yet another example of the low diversity, theropod dominated assemblages typical of strata only a few hundred thousand years younger than the boundary.

Stop 4.7. Cuts in East Berlin and Hampden Basalt, Berlin, CT.

Latitude and Longitude: (aprox.) 41°37.37'N, 72°44.33'W
Tectonostratigraphic Sequence: TS IV
Stratigraphic Unit: East Berlin Formation and Hampden Basalt
Age: Hettangian; ~201.5 Ma
Main Points:

1. Cyclical middle and upper East Berlin Formation
2. Remarkably close match to Towaco Formation
3. Deep-water lacustrine carbonate with dephospatized fish
4. Superb pattern of Van Houten and short modulating cycles
5. "Dead horses" dewatering? structures
6. HFTQ-type quartz basalt of the Hamden Basalt

US 15, and CT 72 reveal over 120 meters of the upper two-thirds of the East Berlin Formation and almost all of the Hampden Basalt (Figures 77, 78).

Almost the entire thickness of the Hampden Basalt is exposed at this stop. The basalt is a high titanium, high-iron, quartz-normative tholeiite (HFTQ) identical in composition and age to the Hook Mountain Basalt of the Newark basin (Puffer et al., 1981). The basalt is typically massive but is vesicular at its base. Tilted pipe stem vesicles are common at the lower contact and indicate a northeasterly flow direction (Gray, 1982). The visible thermal effects of the flows are minimal. The Hampden Basalt is the thinnest of the extrusives in the Hartford basin, reaching a maximum thickness of 30 m.

The lateral continuity of the Van Houten cycles in the East Berlin Formation was demonstrated by Hubert et al. (1976). Three Van Houten cycles are present in the upper part of this section, and they correlate with the three cycles exposed on CT 72 a few hundred meters to the north and the three cycles exposed at the I-91/CT-9 cloverleaf, about 2 km to the east (Hubert et al., 1978). A 35-mthick section of red and minor gray and purple clastics separates these upper cycles from three underlying cycles in the middle East Berlin Formation visible at this stop and CT 72. The uppermost of these three cycles contains a black, microlaminated carbonate called the Westfield fish bed. The Westfield fish bed is the most distinctive bed in the East Berlin Formation, and at all outcrops, it contains a characteristic assemblage of fishes including *Semionotus*, *Redfieldius* and surprisingly common large coelacanths (*Diplurus* cf. *D. longicaudatus*). Correlation of the microlaminae and turbidites in polished slabs from the middle of the fish-bearing carbonate leaves little doubt of the lateral continuity of this units (Olsen, 1988a).

The gray mudstones and gray-black shale beds have generated most of the fossils at these outcrops. The gray units are palynologically productive and have also yielded carbonized leaf and twig fragments of the conifers *Brachyphyllum* and *Pagiophyllum* and the cycadophyte *Otozamites* (Cornet, 1977a). Other fossils include the conchostracan *Cornia* sp., coprolites, articulated but dephosphatized *Semionotus* and *Redfieldius* (in the Westfield fish bed), dinosaur tracks, and burrows and invertebrate trails in various gray and red lithologies (McDonald, 1982, McDonald and LeTourneau, 1988a).

This exposures at this stop provide a superb example of Newark-type lacustrine sequences. The presence of lacustrine cycles in the East Berlin Formation was first recognized by Krynine (1950), with later work carried on by Klein (1968), Hubert and Reed (1978), Hubert et al. (1976, 1978), and Demicco and Gierlowski-Kordesch (1986). The strata are profoundly cyclical and the lake-level cycles document dramatic changes in the depths of the lakes over relatively short periods of time. The Van Houten cycles are virtually identical in form, but not in all fabrics, to the Van Houten cycles described by Olsen from the Towaco Formation (Olsen, 1980c, Olsen et al., 1996b). Fourier analysis of proxies of water depth of this section reveals a clear hierarchy of periodicities in thicknesses of 12.0 m and 68.3 m. Assuming that the 12.0-m-thick Van Houten cycles are the 21,000-year precession cycles, then the 68.3-m-thick short modulating cycles have periodicities in time of 119,000 years. This is a clear hierarchy of cycles similar to that seen in the Lockatong and Passaic Formations. This sequence represents the wet part of a McLaughlin cycle within the wet part of long modulating cycle H1, within the wet part of LaCV1 (Figure 5). The lakes which produced these cycles in the Newark and Hartford basins rose and fell synchronically, controlled by regional climatic change, without necessarily being contiguous bodies of water.

During the deposition TS III of the underlying New Haven Arkose sediment and water supply were from the footwall (east) side of the basin. During Early Jurassic time, in TS IV the drainages reversed with the western hinge side of the basin becoming the source for the bulk of the sediment fill. This can be seen in the cross bedding at this outcrop (LeTourneau and McDonald, 1988). The reversal of drainage probably reflects increased asymmetry of the basin and correspondingly high rates of footwall uplift during an Early Jurassic pulse of increased extension associated with the igneous episode and TS IV. Extensive lacustrine deposition occurred in the Hartford basin only during this period of increased extension. Lacustrine deposition is favored by high extension rates, whereas low extension rates favor fluvial deposition.

The black portions of division 2 of these Van Houten cycles show some of the deformation features common to Newark Supergroup lacustrine strata. Small-scale thrust fault complexes associated with bedding-parallel shear zones are commonly developed in the microlaminated black shales of division 2 of the Van Houten cycles as seen here. At this outcrop and elsewhere in the East Berlin and Towaco formations, black mudstone units above and sometimes within the microlaminated intervals contain what we call "dead horses", small (usually <20 cm long) quadrangular pods of rock composed of laminae and layers oblique to the bedding surface. Similar structures occur in the Eocene Green River Formation and in a variety of other laminated shale sequences (J. Stanley, pers. comm., 1988; M. Machlus, 2002). We interpret the "dead horses" as compacted and dissociated blocks, after the term "horse" for a fault-bounded sliver of rock and their "dead" or dismembered condition. Most commonly, these "dead horses" float in a matrix of massive black mudstone; however, there is a progression from jumbled and partly associated masses of these blocks with no matrix, to isolated blocks in layers composed mostly of matrix. The associated massive mudstone suggests that partial liquefaction accompanied the deformation which produced the dead horses. Beds composed of these black massive mudstones and "dead horses" have usually been interpreted as depositional units, but we interpret them as a form of low-pressure structural mélange.

We suggest that bedding plane-parallel shear lead to three intergradational types of deformation depending on depth of burial and pore-fluid pressure: 1) shallow burial bedding plane shear with the development of plastic folds, duplexes, considerable liquefaction, and the production of "dead horses."; 2) intermediate depth bedding-plane shear with abundant slickenside formation, some brecciation, some mineralization of voids, and small amounts of liquefaction; 3) completely brittle shear with extensive slickensiding and decalcification, with the production of platy, polished horses. All of these structures involve at least small-scale thrust faults and concomitant fault-bend folds. However, the sense of shear of the brittle bedding plane faults is up to the west, consistent with late, probably related to tectonic inversion-related compression (e.g. Withjack et al., 1998). In contrast, the dead horses and associated folding seem to indicate down to the east shear, consistent with syn-rifting tilting. However, all of these structures can easily be confused with "slump" structures, which require a free upper surface, and are usually interpreted as indicators of paleoslope. Although the ultimate tectonic origin of these bedding-parallel shear-related structures is not fully worked out, they cannot be assumed to be related to paleoslope.

Stop 4.8. Silver Ridge, Berlin, CT.

Latitude and Longitude: (aprox.) 41°35.07'N, 72°45.62'W
Tectonostratigraphic Sequence: TS IV
Stratigraphic Unit: New Haven Fm., Talcott Basalt, and Shuttle Meadow Fm.
Age: Hettangian; ~202 Ma
Main Points:

1. Contact between New Have Fm. and Talcott Basalt
2. Triassic-Jurassic Boundary
3. Pillowed Talcott Basalt
4. Volcanoclastic Member of Talcott Basalt and spherules
5. Lower to Middle Shuttle Meadow Formation cyclicity

Silver Ridge is the name given to a gated development to the east of Silver Lake and CT. Route 15. Roughly 230 m of New Haven Fm., Talcott Basalt, and lower to Shuttle Meadow Fm. are patchily exposed in a series of exposures created in the course of construction for the development and attendant highway improvements and unrelated light industry (Figure 79). We will visit a variety of locations in this general area that illustrate some of the main features of this area.

Stop 4.7a. Uppermost New Haven Formation and lower, pillowed Talcott Basalt at cut on east side of CT Rt. 15.

This cut reveals the uppermost meter of the New Haven Formation of TS IV and 10 meters of the basal Talcott basalt. Here the uppermost New Haven Formation is predominately gray sandstone with subordinate amounts of siltstone. The sandstone contains plant stem and branch compressions and the fine thin bedded sandstones and siltstone contain abundant plant foliage and reproductive structures, so far predominately conifer shoots and cone fragments. This is a weathered version of the gray, uppermost New Haven Formation seen in cores Silver Ridge B-2 and B-3 taken to the immediate southeast and seen at stop 3.3a. The exposed New Haven Formation should be of very earliest Jurassic age, although we await confirmation of this though palynological analysis.

The basal Talcott formation is heavily pillowed here, but this will be better seen at the next location (see below). There are no visible signs of thermal metamorphism at this site, which is typical of contacts between pillowed basalt flows and sedimentary units. Thus the pollen preservation should be good.

Stop 4.7b. Lower, pillowed Talcott Basalt in cut in back of light industrial building.

About 20 m of the spectacularly pillowed lower Talcott basalt is exposed at this locality. To my knowledge there are no formal studies of this exposure.

Stop 4.7c. Volcanoclastic member of the Talcott Basalt.

The Talcott basalt is a complex of pillowed to massive flows interbedded with volcanoclastic beds and subject to abrupt lateral changes in facies. Davis (1889) described what he termed ashes in Talcott Basalt in this area and one exposure of these can be seen here. This volcanoclastic sequence occurs near the top of the Talcott basalt and contains some sedimentary admixture. It is apparently equivalent to the volcanoclastic beds seen in the Silver Ridge B-1 core (Stop 3.3b).

In addition to the polymict basaltic clasts and palagonitic matrix, numerous spherules can be seen on several bedding planes. These have been called lapilli, but their true nature is unknown. To the south of here, the Talcott cuesta rises to a much higher elevation. Excavation for houses shows that the Talcott has an upper massive basaltic flow where the ridge is higher, underlain by volcanoclastic beds and then more massive to pillowed basalt. This upper flow must disappears rapidly to the north and northeast but it is unknown whether the flow disappears because of erosion or non-deposition. It is also unknown how much of the volcanoclastic beds are ash fall beds or reworked eruptive spatter or lappilli, or just reworked eroded basalt. There are no modern studies of these volcanoclastic beds.

Stop 4.7d. Lower Shuttle Meadow Formation.

This exposure of predominately gray mudstones and sandstone, along the east side of the road, is probably the regressive part of the lower, limestone-bearing Van Houten cycle of the lower Shuttle Meadow Formation. It is instructive to note that even though we have fairly good exposures in this area (by Hartford basin standards) the basic cyclostratigraphy of the lower Shuttle Meadow Formation could not be worked out without continuous core. My attempts at doing so prior to the coring of the Silver Ridge B-1 core were incorrect and misleading.

Stop 4.7e. Middle Shuttle Meadow Formation.

These disturbed exposures show the middle Shuttle Meadow Formation. Silver Ridge B-1 was spudded just to the north. Peter LeTourneau and I had hoped we would intersect a distinctive nodular limestone sequence that was supposedly in the middle of the formation but had never actually been seen in unambiguous superposition with the cyclical lower Shuttle Meadow. Silver Ridge B-1 was apparently spudded below this limestone, which much to our pleasure was subsequently excavated at this site. The limestone level apparently lies a few meters above the top of the Silver Ridge B-1 core (Figures 67, 79).

The limestone beds consist of decimeter-scale nodular gray to purple micrite and gray to purple mudstone and siltstone. Semionotid fish scales, bones, and coprolites are fairly common. Some of the flaggier associated siltstone beds and ripple-cross laminated siltstones have reptile footprints. What is probably the same beds on Higby Mountain to the east have produced numerous unionid bivalves, scales and bones of *Semionotus* and a partial skull and associated bones of a large coelacanth (*Diplurus* cf. *D. longicaudatus*) (McDonald, 1992). Limestone beds, certainly representing the same level are seen at Plainville, CT in Cooks Gap o the north and to the south along US Rt. 1 in Branford, CT a distance of over 100 km (Olsen et al., 1996b). Evidently, while this limestone was deposited by a relatively shallow lake, the lake was very large in area. These limestone beds are called the Plainville limestone and represent the wet phase (division 2) of one or two Van Houten cycles in the wet phase of a short modulating cycle, in the drying phase of a McLaughlin cycle.

END OF FIELD TRIP

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Figure 1. The Newark basin within the Newark Supergroup. **A**, Newark Supergroup: **1**, Newark basin; **2**, Hartford (below) and Deerfield (above) basins; 3, Dan River basin; 4, Farmville and associated basins; 6, Richmond and mostly buried

Taylorsville basins; 7, Culpeper basin; 8, Gettysburg basin; 9, Pomperaug basin; 10, Deep River basin; 11, Fundy basin; 12, mostly buried Chedabucto or Orpheus basin (modified from Olsen, 1997). **B**, Newark basin and lithostratigraphic divisions (modified from Olsen et al., 1996a). Stops are: **1**, 1.1; **2**, 1.2; **3**, 1.3; **4**, 1.4; **5**, 1.5; **6**, 1.6; **7**, 1.7; **8**, 1.8; **9**, 1.9; **10**, 2.1; **11**, 2.2; **12**, 2.3; **13**, 2.4; **14**, 2.5; **15**, 2.6; **16**, 2.7; **17**, 3.1; **18**, 3.2; **19**, 3.3.

Figure 2 Hartford and Deerfield basins of Connecticut and Massachusetts shown positions of field stops.

Figure 3. 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 4. 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).

Figure 5. Newark and Hartford basin section and combined time scale showing distribution of field stops (adapted from Olsen and Kent, 1999; Olsen et al., 2001a; Olsen et al., 2002b)

Figure 6. Van Houten and compound cycles (modified from Olsen and Kent, 1999).

Figure 7. 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 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.

Figure 9. Representative vertebrates from Tectonostratigraphic Sequence IV of the Newark basin (modified from Olsen, 1988; Olsen and Flynn, 1989): **A**, the palaeonisciform *Redfieldius* (Feltville and Boonton fms.); **B**, the palaeonisciform *Ptycholepis marshi* (Feltville and Boonton fms.); **C**, the holostean *Semionotus* (simple scale group) (Feltville and Towaco fms.); **D**, the holostean *Semionotus* tenuiceps (Feltville and Towaco fms.); **E**, the holostean *Semionotus elegans* (Towaco and Boonton fms.); **F**, the large coelacanth *Diplurus longicaudatus* (Boonton Fm.); **G**, the synapsid track *Ameghinichnus* (Towaco Fm.); **H**, the lepidosaur track *Rhynchosauroides* (Passaic and Towaco fms.); **I**, the crocodyomorph track *Batrachopus deweyii* (Passaic - Boonton fms.); **J**, the ornithischian dinosaur track *Anomoepus scambus* (Feltville - Boonton fms.); **K-M**. *Grallator* spp. (Passaic - Boonton fms.); **N-O**, *Anchisauripus* spp. (Passaic - Boonton fms.); **P-Q**. *Eubrontes giganteus* (Passaic - Boonton fms.). Scale is 1 cm except in **H** where it is 5 mm.

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).

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).

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.

Figure 13. Composite section of Lockatong in vicinity of the Hudson River, northeastern Newark Basin 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 5 and for northeast composite in Figure 19.

Figure 14. Anticline at Greenbrook Falls, Stop 1.1b. Prominent dark band is grey mudstone at 4 m in section in Figure 32.

Figure 15. Measured section at Greenbrook Falls, Stop 3b (modified from Parker et al., 1988).

Figure 16. 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 17. Composite stratigraphic section at Ross Dock with distribution of fossils. From Olsen (1980b).

Figure 18. 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 19. **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 22. 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**, Comparison 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 21 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. **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 22 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).

Figure 23. Exposures along Henry Hudson Drive, Stop 3c near Ross Dock showing cycles W5 and W6: *a*, nodular probable caliche horizon.

Figure 24. Quarry face at Stop 3d, with olivine zone (*ol*) in zone of deflected columns.

Figure 25. Mostly concordant contact of Palisade sill with mudstone and arkose of Lockatong Formation just north of the George Washington Bridge at Stop 3e.

Figure 26. 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 27. *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).

Figure 28. Section and fossils at Granton Quarry, Stop 5 (modified from Olsen, 1980b).

Figure 29. Exposures of copper-bearing white and tan sandstone surrounding purple siltstone of lower ?Kilmer Member at Stop 6, Lyndhurst, New Jersey.

Figure 30. 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*.

Figure 31 Section at Stop 1.6, type section of the Feltville Formation and correlation to ACE core PT-26 and NBCP Martinsville no. 1 core.

Figure 32 Example of the fern *Clathropteris meniscoides* in growth position from Stop 1.6.

Figure 33. 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 footprint in which the actual surface in contact with the foot was a centimetre 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).

Figure 34. Examples of footprints from the Feltville Formation: A, small leptodactylus examples of ?*Anomoepus* from the upper Feltville of the Dock Watch Quarry, Martinsville, NJ; B, natural mould of a normal track of *Anomoepus crassus* from the upper Feltville of the Shrump Quarry, Roseland, NJ; C, faint (water washed) natural mould of a normal track of Anchisauripus sp., from the lower Feltville (transgressive portion of the upper-limestone bearing cycle, Blue Brook, Martinsville

Figure 35 Examples of the holostean fish *Semionotus* from the Feltville Formation: A, *Semionotus tenuiceps* group from the upper limestone bearing cycle at Martinsville, NJ; B, *Semionotus* sp., from the lower limestone bearing cycle at the Watchung Reservation, Stop 1.6; C, gibbose *Semionotus* sp., from the upper limestone bearing cycle at Martinsville, NJ.

Figure 36. Pattern of distribution of *Semionotus* species through the history of the Newark basin. The diversity of *Semionotus* found in the Late Triassic Lockatong Formation (cycle W-5 of Olsen, 1980c), and three Early Jurassic sedimentary formations: the Feltville, Towaco (cycle P4), and the Boonton formations. Each of these four faunas is from a single sedimentary cycle. Each fish represents the occurrence of a species. Thus, in the Lockatong Formation, there are 2 species of

Semionotus; there are 6 in the Feltville, 21 in the Towaco and 9 in the Boonton. Species in each cycle are further grouped by their morphology of dorsal ridge scales as illustrated in the column headings: A, simple scale group; 1l, modified simple scale group; C, small scale group; D, thin-spined scale/*S. micropterus* group; E, globular scale; F, robust scale/*S. tenuiceps* group; G, concave scales/*S. elegans* group; H, dorsal ridge scale group. Species occurring in more than one cycle are numbered 1-6 and are presumed colonists. Unnumbered species in each cycle are unique (thus far) and are tentatively considered to be endemic. From McCune in Olsen et al. (1989).

Figure 37. 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).

Figure 38. 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 39. 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).

Figure 40. 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 41. 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 b-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.

Figure 42 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*. **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).

Figure 43. Theropod dinosaur footprints from the Towaco Formation (mostly of the Riker Hill quarry). A, Natural cast of left pes of very small, *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 *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).

Figure 44. Baby dinosaur tracks and "*Hyphepus*". **A**, Natural cast of several trackways of very small Anomoepus, upper unit 18, Walter Kidde Dinosaur Park (John Colegrande collector, John Colegrande collection) (same slab as Figure 62A) (scale, 1 cm). **B**, Large slab of natural casts of numerous trackways of small individuals and one larger individuals of *Anomoepus* suggestive of herding, upper unit 18, Walter Kidde Dinosaur Park, specimen destroyed (scale, 10 cm). **C**, Sitting tack of very small *Anomoepus*, upper unit 18, Walter Kidde Dinosaur Park (John Colegrande collector, John Colegrande collection) (same slab as Figure 60Aa) (Scale, 1 cm). **D,** Extremely small underprints of *Anomoepus*, Riker Hill quarry (Robert Salkin collection) (Scale, 1 cm). **E**, Extremely small leptodactylus trackway of *Grallator*, Riker Hill quarry (Robert Salkin collection) (Scale, 1 cm). **F,** Example of what would be called *Hyphepus* sp., but is more likely a distorted example of *Grallator* Riker Hill quarry (Robert Salkin collector, Robert Salkin collection).

Figure 45. *Anomoepus* from the Towaco Formation of the Riker Hill quarry. **A**, Natural cast of very small left pes of, upper unit 18, Walter Kidde Dinosaur Park (John Colegrande collector, John Colegrande collection) (same slab as Figures 61A). **B**, small right pes, Riker Hill quarry, specimen lost. **C**, Natural cast of small pes upper unit 18, Dinosaur Park, ECPC 38. **D**, Natural cast of large left pes upper unit 18, Dinosaur Park; specimen donated to Copenhagen Museum of Natural History, Copenhagen, Denmark. Same bedding surface as E, J and L. **E**, Natural cast of right and left pedes, upper unit 18, Walter Kidde Dinosaur Park, ECPC 5 (?lost). **F**, Natural cast of right manus with skin impressions. **G**, Natural cast of left pes with skin impressions (see inset). H, Right pes with very fine skin impressions (see inset), unit 5, Walter Kidde Dinosaur Park (Charles Rizzo collector, Charles Rizzo collection). Scale for A-H is 1 cm. **I**, Trackway of small individual, upper unit 18, Walter Kidde Dinosaur Park (specimen lost) (scale, 1 cm). **J,** Natural cast of trackways of large and small *Anomoepus* and an indeterminate footprint form, upper unit 18, Walter Kidde Dinosaur Park, uncatalogued AMNH specimen (scale, 10 cm). **K**, Trackway, same slab as Figure 11N, Riker Hill quarry, collector and disposition unknown (scale 1 cm). **I**, *In situ* trackways, mostly of *Anomoepus*. Impressions of E (above) are just to left of hammer; and impressions of tracks in J (above) are above and to the left of hammer (hammer is about 1 ft long).

Figure 46. 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).

Figure 47. 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).

Figure 48 Fluvial sequences in the Prallsville Member of the Stockton Quarry as seen at Stop 2.1.

Figure 49 Exposures along NJ Rt. 29 at Byram, NJ and small adjacent creek (containing the type sections of the Byram and Tohickon members) at Stop 2.2, comparison with Nursery no. 1, and exposures of the Lockatong Formation in the Haines and Kibblehouse Quarry (containing the type section of the Skunk Hollow Member), Hilltown Township, PA. *SHFB*, indicates the Skunk Hollow Fish bed. For lithology key see Figure 5.

Figure 50 Two end members of the cycle types seen at Stop 2.2. (A) Corresponds to Van Houten's (1964) detrital cycle type, whereas (B) corresponds roughly to Van Houten's chemical cycle type. Key to lithology on right. From Olsen et al. (1989).

Figure 51 Member C and Warford Member of the Passaic Formation at the type (Stop 2.3) and correlative sections. Section 2 is a composite based on: a, the type section along Warford Brook (Stop 2.3); b, section along Smithtown Creek; c, section exposed along NJ Rt. 29 (Stop 2.3), Kingwood Station, NJ. Section 3 is along tributary to Nishisakawick Creek, Palmyra, NJ; and section 4 along Longview Rd., Linfield, PA. *F*, marks the position of the fish bearing cycle of the Warford Member. For lithology key see Figure 5.

Figure 52 Measured section of the Passaic Formation at Pebble Bluff, Stop 2.4, showing the interfingering of debris flow, shoreline, and perennial lake deposits. From Olsen et al. (1989).

Figure 53 Lateral correlation of the lower part of the Perkasie Member in outcrops and cores. Locations of sites are: 1, Rt. 18, New Brunswick, NJ ; 5, NE extension, PA Turnpike, Tylersport, PA; 6, quarry, Sanatoga, PA; 7, road outcrops in and near Milford, NJ; 8, Pebble Bluff, Holland Township, NJ (Stop 2.4) (from Olsen et al., 1996a). For lithology and magnetic polarity key see Figure 5.

Figure 54 Examples of tracks from the Smith Clark Quarry, Perkasie Member, Milford, NJ: A, *Atreipus sulcatus*; B, *Brachychirotherium parvum*. From Baird (1957).

Figure 55 Measured section of one complete Van Houten cycle and two partial cycles within the Metlars Member of the Passaic Formation exposed at Stop 2.5. Key to section as follows: A, rooted, massive red mudstone of division 3 of lowermost cycle; B, rooted, massive gray mudstone of division 1 (transgressive unit) of middle cycle; C, oolitic sands encasing stromatolitic tufa-coated tree stumps; D, black and gray mudstone interbedded with burrowed oscillatory-rippled sandstone, with mudcrack density increasing upsection; E, red massive sandstone with minor massive, mudcracked mudstone; and F, rooted, red massive mudstone of division 1 of overlying cycle. This cycle corresponds to the lowest black shale-bearing cycle in the member.

Figure 56 Correlation of the Pioneer Crossing site and the Somerset no. 1 core. Paleomagnetic determinations by D. Kent (pers. comm., 2001). Arrow points to level seen at Stop 2.6.

Figure 57 Vertebrate footprints from the Pioneer Crossing tracksite: A, *Atreipus milfordensis* manus-pes set; B, *Grallator* sp.; C, *Atreipus milfordensis* manus-pes set; D, *Grallator* sp.; E, *Chirotherium lulli* partial trackway; F,

?*Brachychirotherium* sp. Pes; G, *Rhynchosauroides* sp.; H, small indeterminate quadruped manus-pes set. Scales is 1 cm. From Szajna and Hartline (2002).

Figure 58 Map of the Jacksonwald syncline showing the positions of the sections discussed in text. Locations for the four sections shown in figure 8 are as follows: GM, Grist Mills (Late 40°18.85 Long. 075°51.20); I, Section I (Lat. 40°18.76 Long. 075°50.56); II, Section II (Late 40°18.76 Long. 075°50.55); III, Section III (Late 40°18.81 Long. 075°50.38). Other paleontological localities are: 1, Exeter Golf Course Estates (Feltville Fm. locality for *Eubrontes giganteus*); 2, original palynological boundary sections of Cornet (1977) and Fowell (1994); 3, Wingspread footprint locality of Silvestri and Szajna (1996); 4, "Pine Ridge creek" locality for pollen and footprints; 5, Pathfinder Village bone assemblage in member TT (discovery site at (Late 40°18.55 Long. 075°50.10); 6, Walnut Road phytosaur tooth locality in member SS; 7, Shelbourne Square (Ames) footprint locality of Szajna and Silvestri (1993) and Silvestri and Szajna (1993); 8, Heisters Creek development footprint locality; 9, Tuplehocken Road footprint locality; 10, pollen localities OLA1 and OLA3 of Cornet (1977). Specific latitude and longitude coordinates not given here are listed in Olsen et al. (2001b).

Figure 59 Details of three Triassic-Jurassic boundary sections. The numbers and letters next to columns refer to various fossil producing levels (see Olsen et al., 2002b).

Figure 60 Comparison of the Triassic-Jurassic boundary at stop 2.7 an the K-T boundary in the Raton Basin, Colorado: *bc*, boundary clay; C, Cenozoic gray shale; *cl*, coal and carbonaceous shale; K, Cretaceous gray shale; *smcl*, smectitic claystone. Note that strata dip 60° to north (left) at Stop 2.7.

Figure 61 Iridium and aluminium concentrations at the four sections along strike in the Jacksonwald syncline (Figure 58). Section on left is the average section (Fig. 9), and *bg*, indicates position of the "blue-gray sandstone".

Figure 62 Example of a large slab of grallatorid (theropod dinosaur) and *Brachychirotherium parvum* (rauisuchian) track. *Brachychirotherium parvum* is a typical Triassic form and this slab occurs with 30 ky of the boundary.

Figure 63 Earliest Jurassic age reptile footprints from the uppermost Passaic Formation of the Montclair to Patterson, NJ area: A-C, *Rhynchosauroides* n. sp.; D-E, *Batrachopus deweyii*; F, trackway of medium-sized *Anchisauripus sillimani*; G, Large *Grallator* sp.; H, medium-sized Anchisauripus sp.; I, *Grallator tuberosus*; J, *Eubrontes giganteus.*

Figure 64 Overlap zone between Titusville and Rutgers cores and type sections of members I to L-M, and the Perkasie Member. Cores on display are the interval marked with arrows. Sections that make up the Ottsville section (3) are: a, section in Bucks County Crushed Stone Quarry and adjacent Rapp Brook (the type section); b, section along PA Rt. 611, Ottsville, PA, polarity data from McIntosh and others (1985) and Hargraves (pers. comm.)(see Olsen, 1988a). Type section for member L-M is a composite: c, east side of Rapp Brook; d, west side of Rapp Brook. For lithology and magnetic polarity key see Figure 5.

Figure 65 Overlap zone between Rutgers and Somerset cores and type sections of the Kilmer, Livingston, and Metlars members in Piscataway, NJ. For lithology and magnetic polarity key see Figure 5. Cores on display are the interval marked with arrows.

Figure 66 Comparison between cores ACE cores C-92 and PT-26.

Figure 67 Comparison between core B-1 from the lower Shuttle Meadow Formation and ACE core Pt-26 from the Newark basin.

Figure 68 Lower New Have Formation at Cheshire, CT (from McInerney and Hubert, 2002).

Figure 69 *Erpetosuchus* sp. From the New Haven Formation of Cheshire, CT: above, reconstructed partial skull; below, reconstruction of galloping animal.

Figure 70 Examples of the fern *Clathropteris meniscoides* from Stop 4.2, Holyoke, MA, possible Triassic-Jurassic boundary section. Photo by B. Cornet.

Figure 71 Upper New Haven Formation and lower Shuttle Meadow Formation, I 91 cut, Northampton, MA.

Figure 72 Stratigraphy of the lower Portland Formation. A, Park River Cores; B, South Hadley Falls; C, Chicopee River; D, Westfield River; E, Stony Brook/ Connecticut River. Note position of Stop 4.5.

Figure 73 Detailed map of the dinosaur trackways at the main slab of the Holyoke Footprint Preserve site (Stop 4.5) (from Ostrom, 1972). Arrows indicate the general trends and the numerical designations assigned to individual trackways, mostly of *Eubrontes giganteus*. Solitary prints (encircled) that probably represent continuations of the above trackways are designated by letter. Isolated print #413 is presumed to be distinct from all other trackways and accordingly is designated b`' number. Small open circles indicate former positions of removed or destroyed footprints. Questionable prints are outlined by dashed lines (caption modified from Ostrom, 1972).

Figure 74 Type specimen of *Eubrontes giganteus* from Stop 4.5 and described by Hitchcock in 1836.

Figure 75 Original set of trackways of *Eubrontes giganteu s* exposed at Dinosaur State Park. Inset is natural cast of a single *Eubrontes giganteus*. From Farlow and Galton, 2002.

Figure 76 Drawing of trackways of *Eubrontes giganteus* as they are now exposed. This slab is adjacent to the one shown in Figure 75, which is now buried and protected. From Farlow and Galton (2002).

Figure 77 Composite photograph of the section exposed at Stop 4.7. Vertical exaggeration is 2 x.

Figure 78 Section exposed at Stop 4.7. From Olsen et al. (1989).

Figure 79 Section at Stop 4.8, Silver Ridge, based on cores B-1, B-2 and exposures.

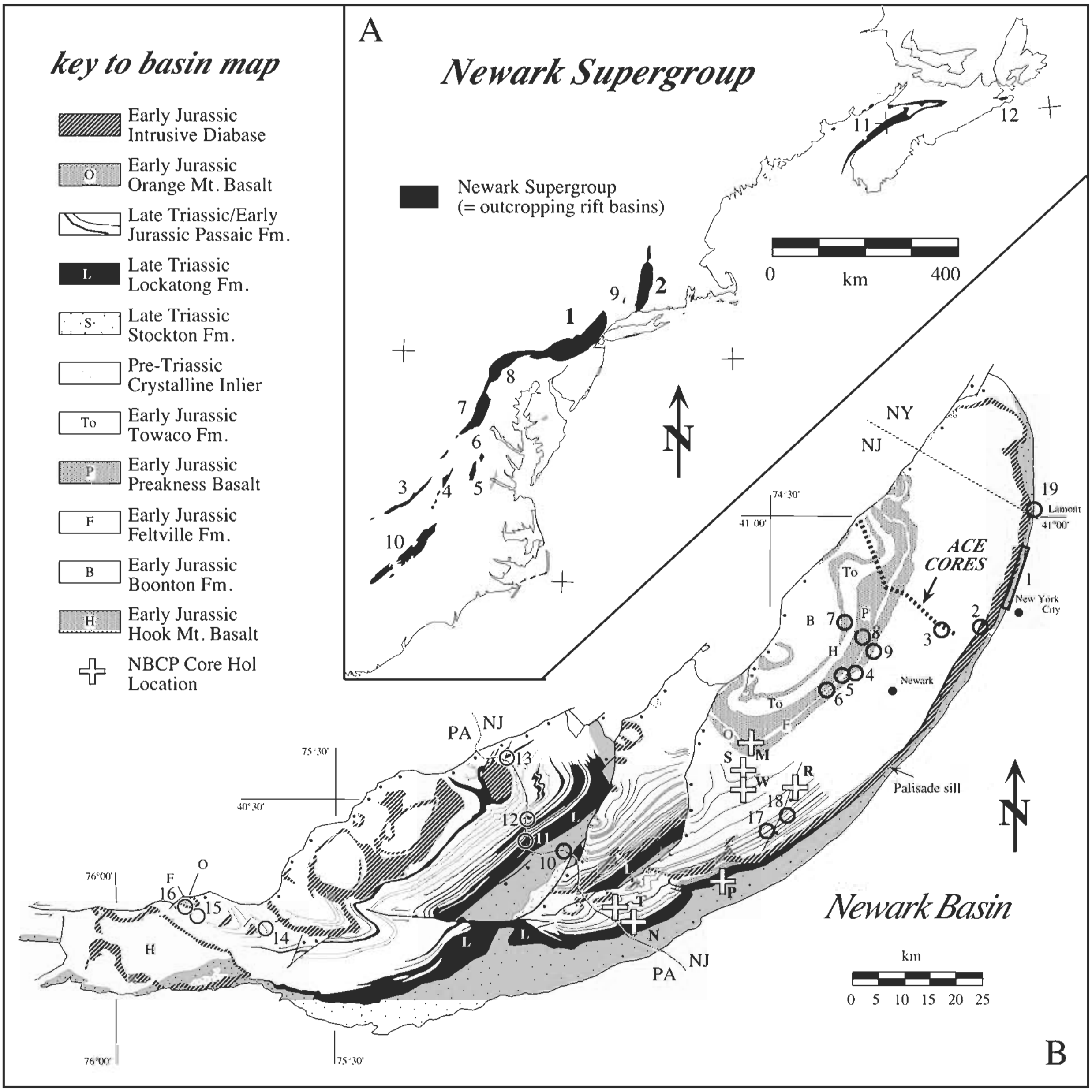

key to basin map
Early Jurassic Intrusive Diabase
Early Jurassic Orange Mt. Basalt
Late Triassic/Early Jurassic Passaic Fm.
Late Triassic Lockatong Fm.
Late Triassic Stockton Fm.
Pre-Triassic Crystalline Inlier
Early Jurassic Towaco Fm.
Early Jurassic Preakness Basalt
Early Jurassic Feltville Fm.
Early Jurassic Boonton Fm.
Early Jurassic Hook Mt. Basalt
NBCP Core Hol Location
A
Newark Supergroup
Newark Supergroup (= outcropping rift basins)
0 km 400
ACE CORES
New York City
Newark
Lamont
Palisade sill
Newark Basin
km
0 5 10 15 20 25
NY
NJ
PA
B

Figure 1

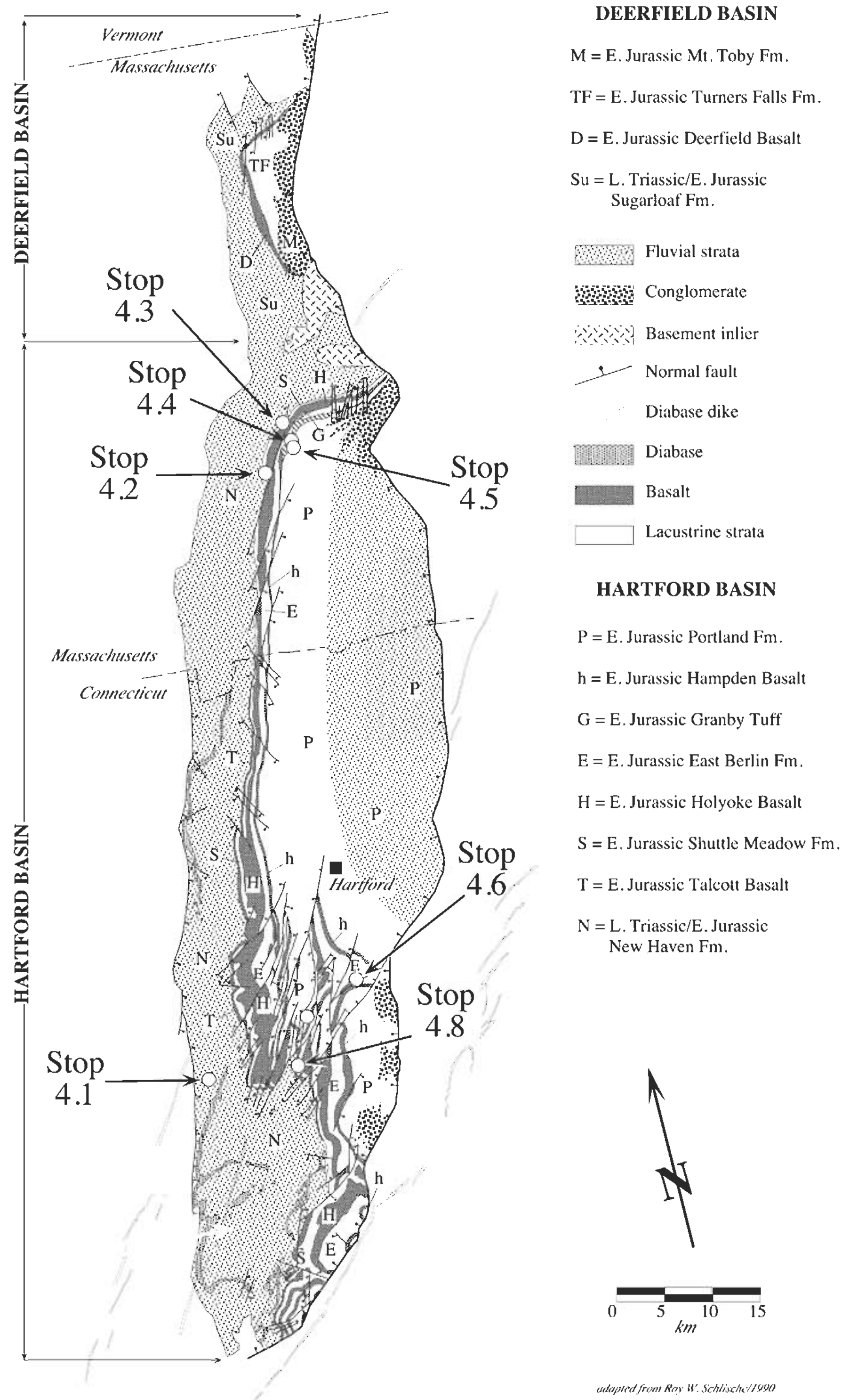
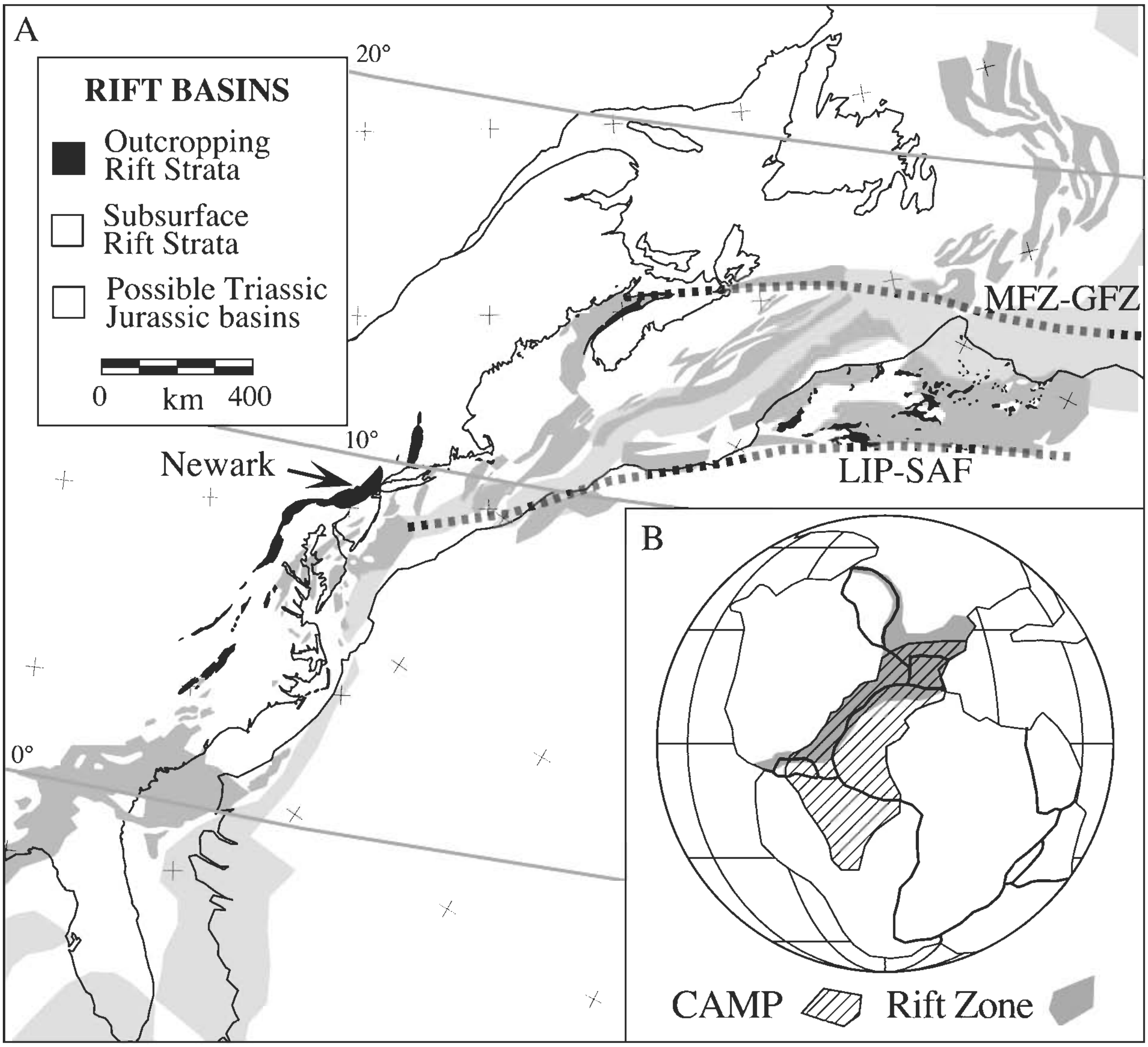


Figure 2. Hartford basin.



A
RIFT BASINS
Outcropping Rift Strata
Subsurface Rift Strata
Possible Triassic Jurassic basins
0 km 400
20°
10°
0°
Newark
MFZ-GFZ
LIP-SAF
B
CAMP
Rift Zone

Figure 3

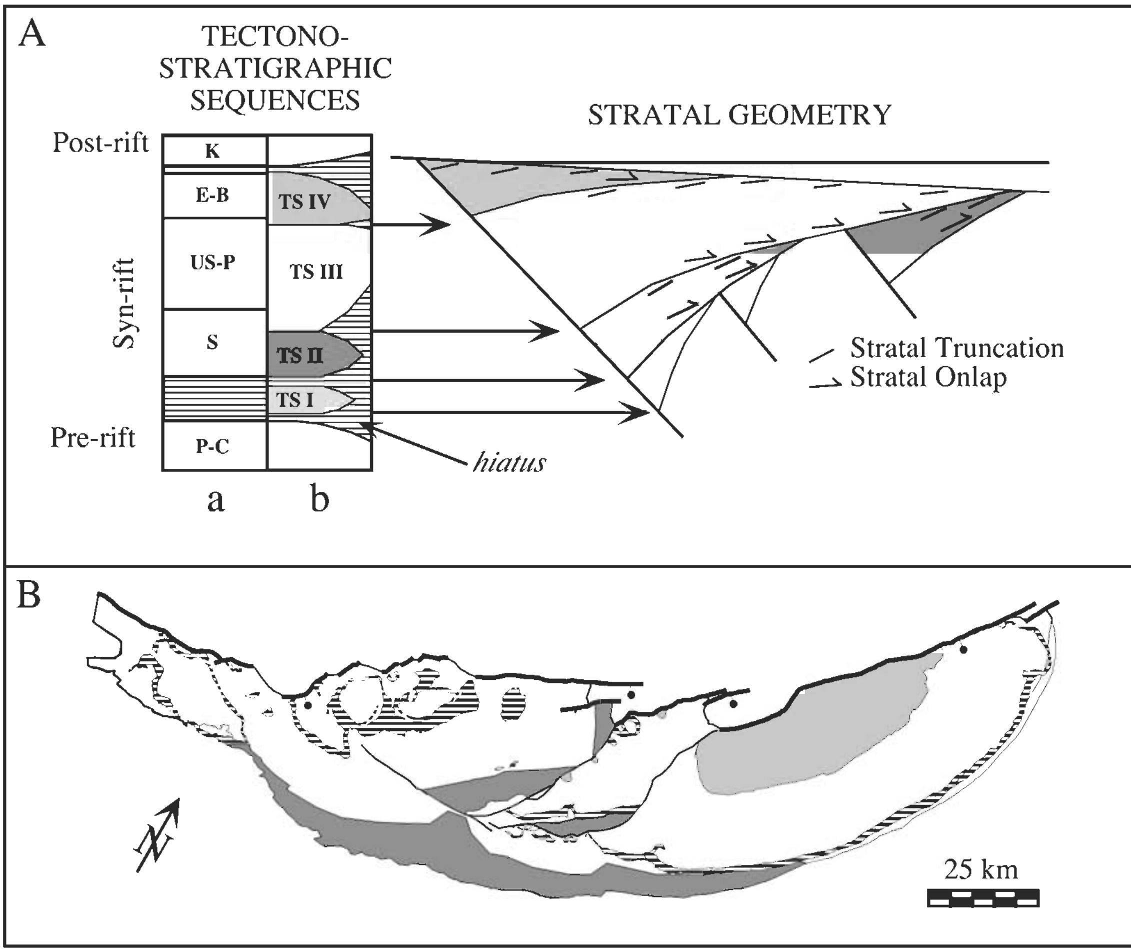


Figure 4. Tectonostratigraphic Sequences.

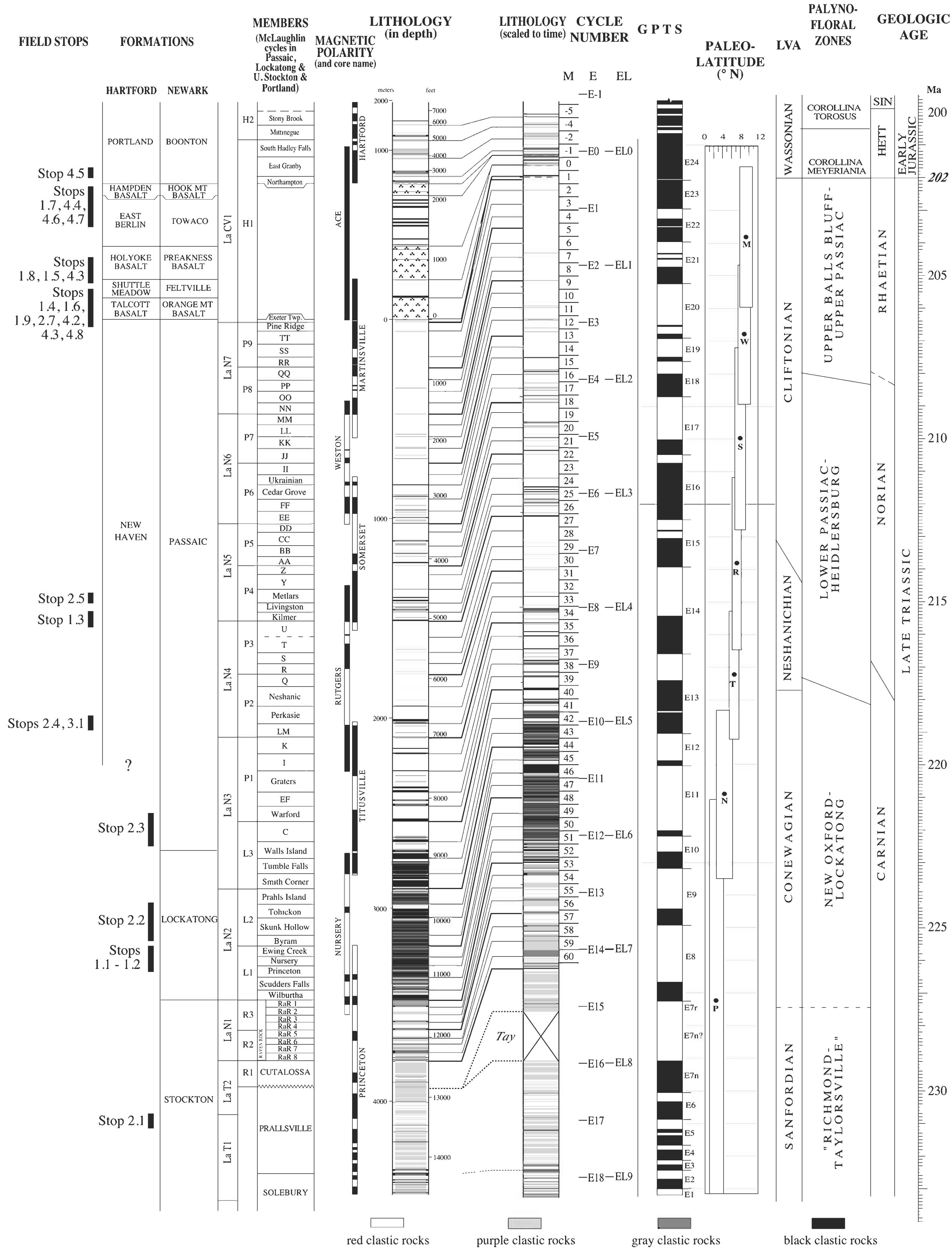


Figure 5. Newark and Hartford Basin Timescale.

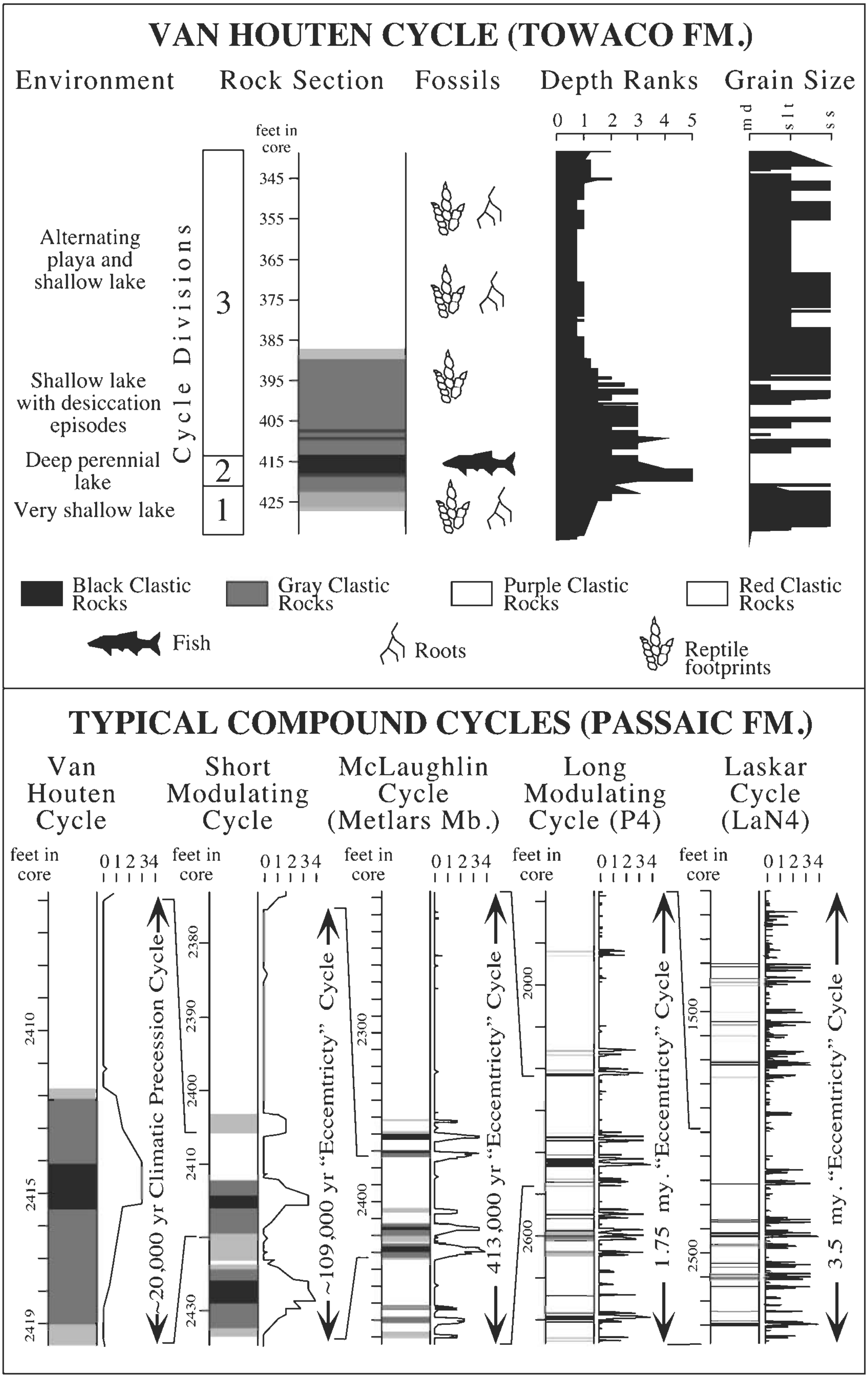


Figure 6. Cycles

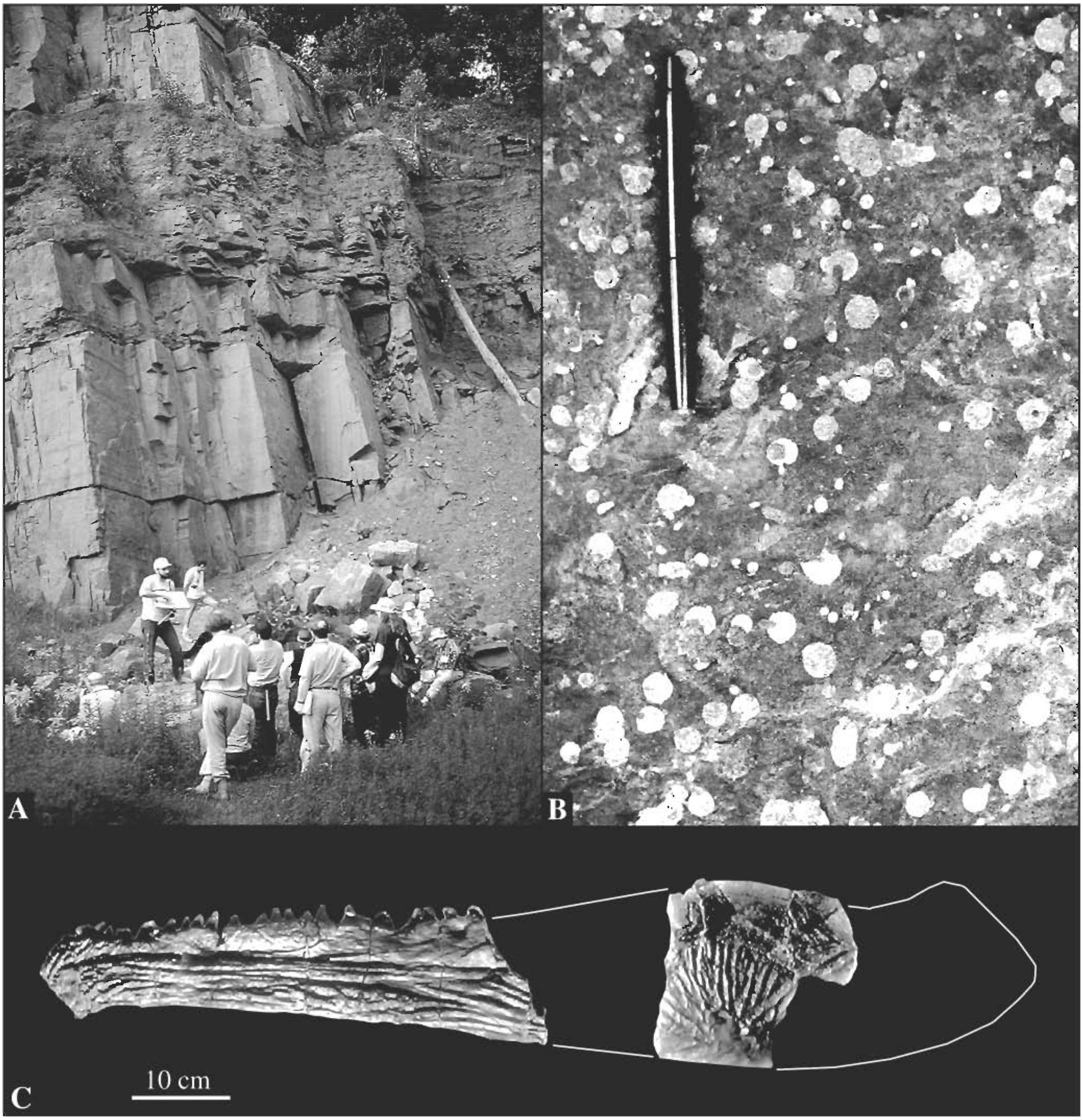


Figure 7. Stockton (TS II) outcrops and fossils.

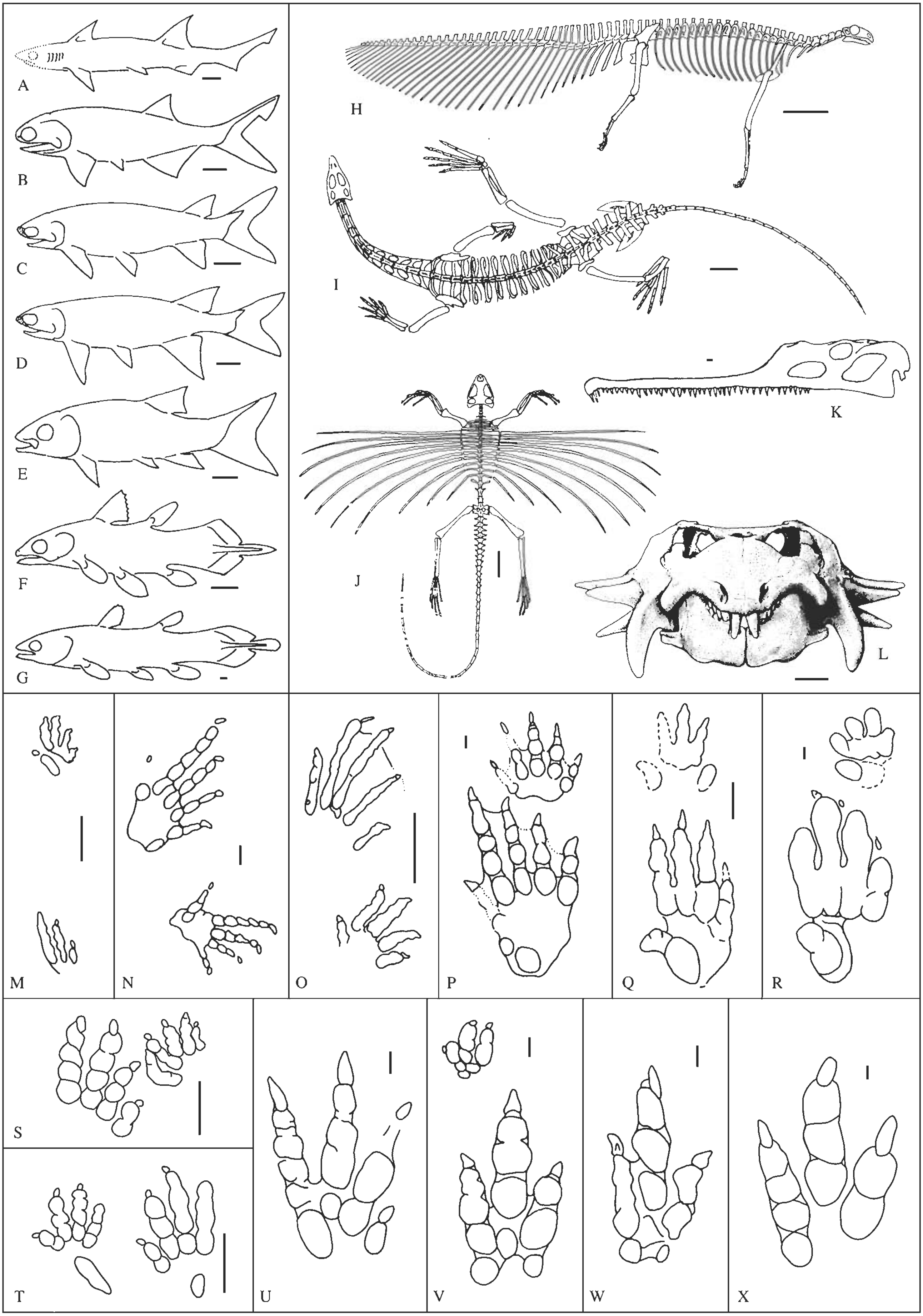


Figure 8. Vertebrates of TS III.

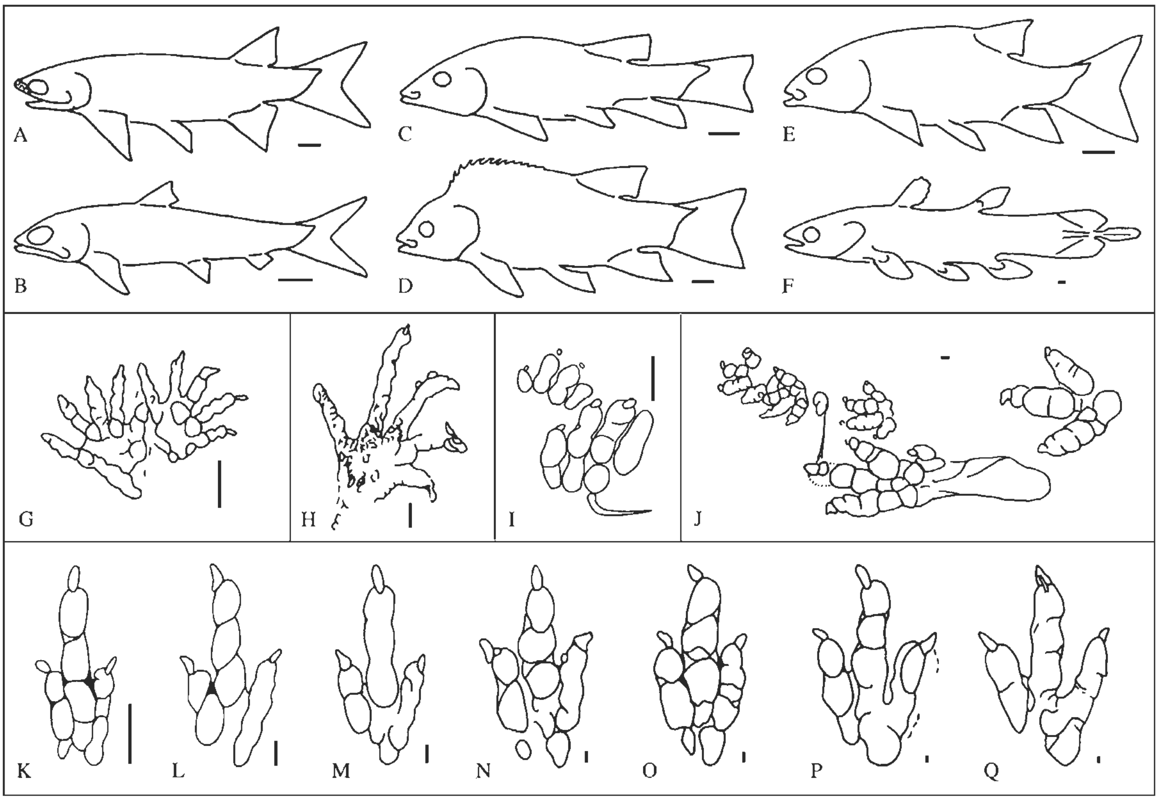
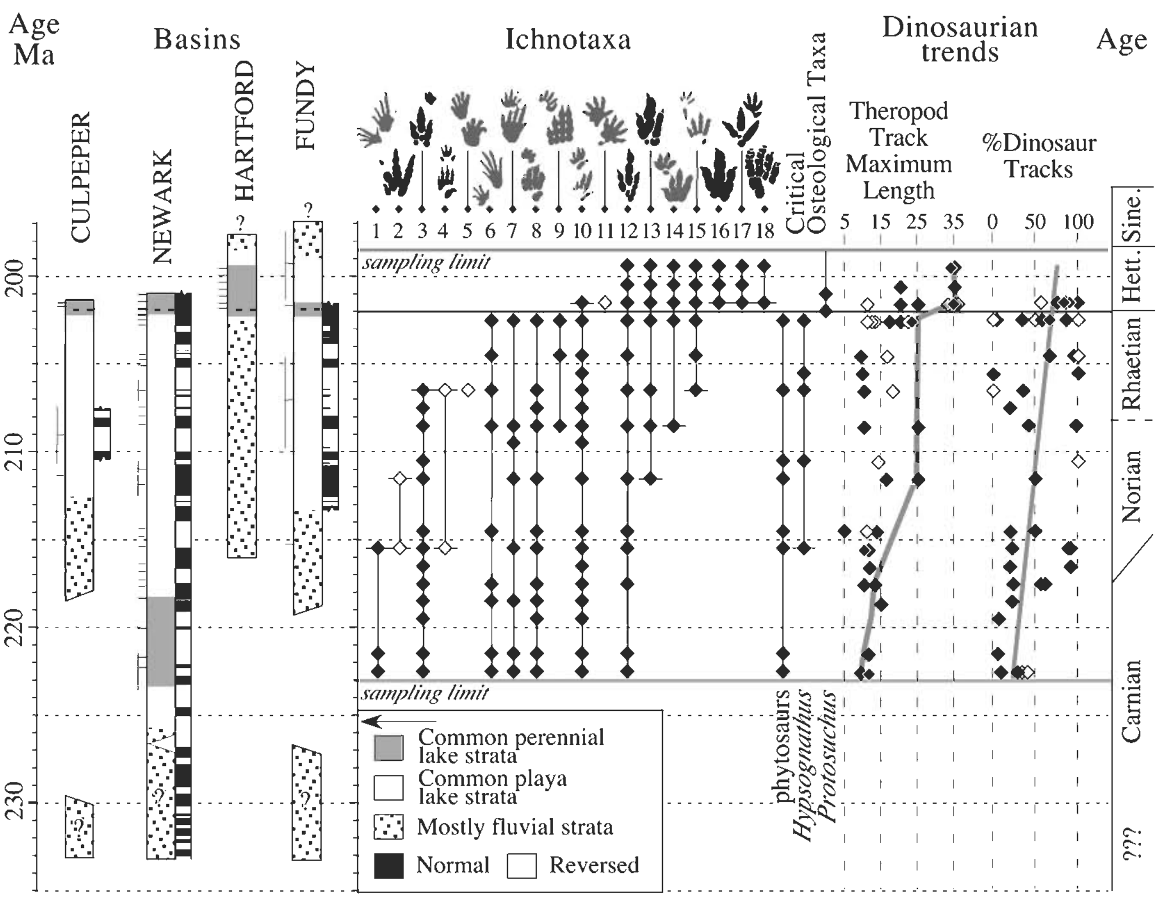


Figure 9. Vertebrates of TS IV.

Figure 10. Ranges of Footprint Taxa.



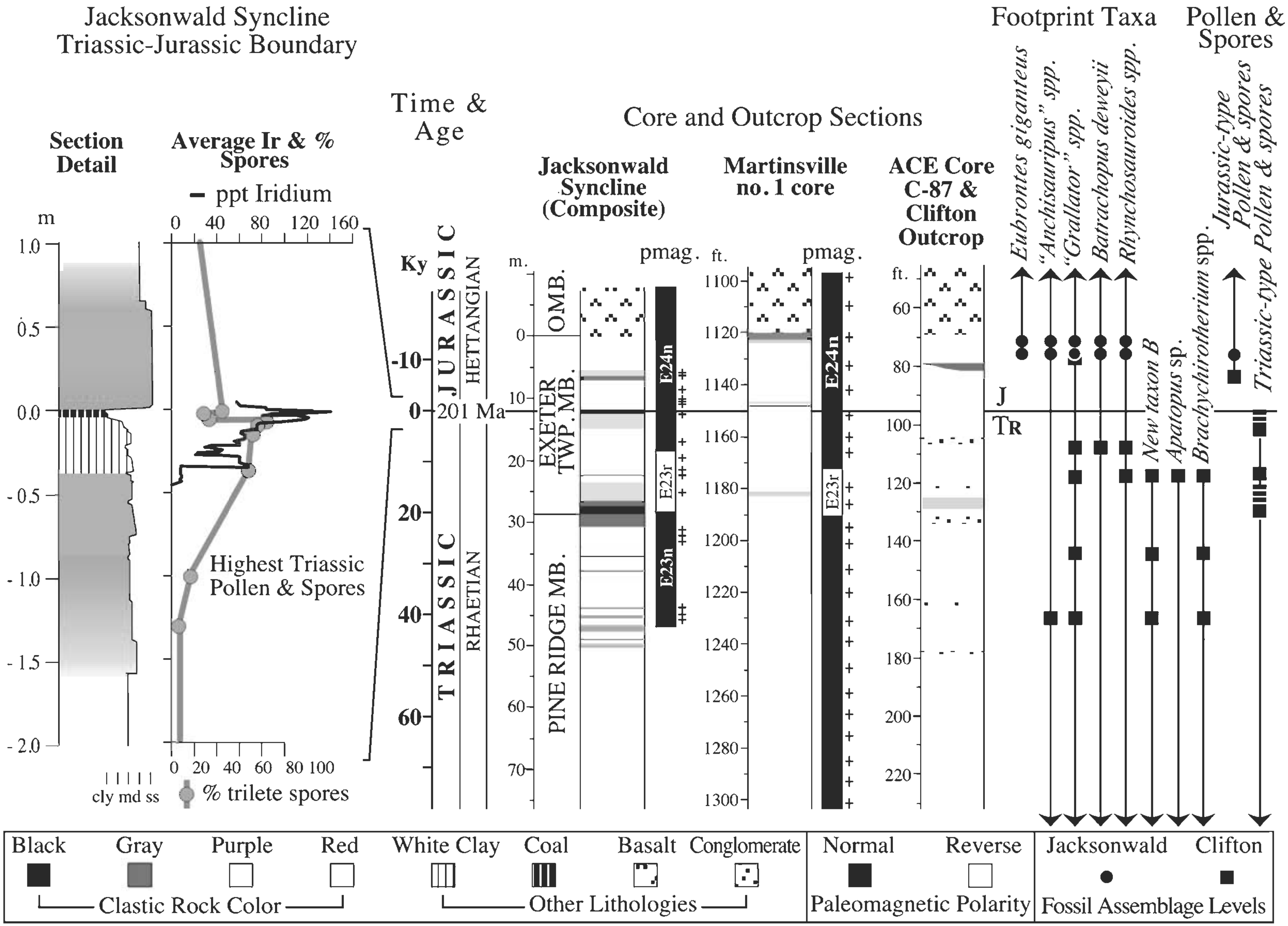
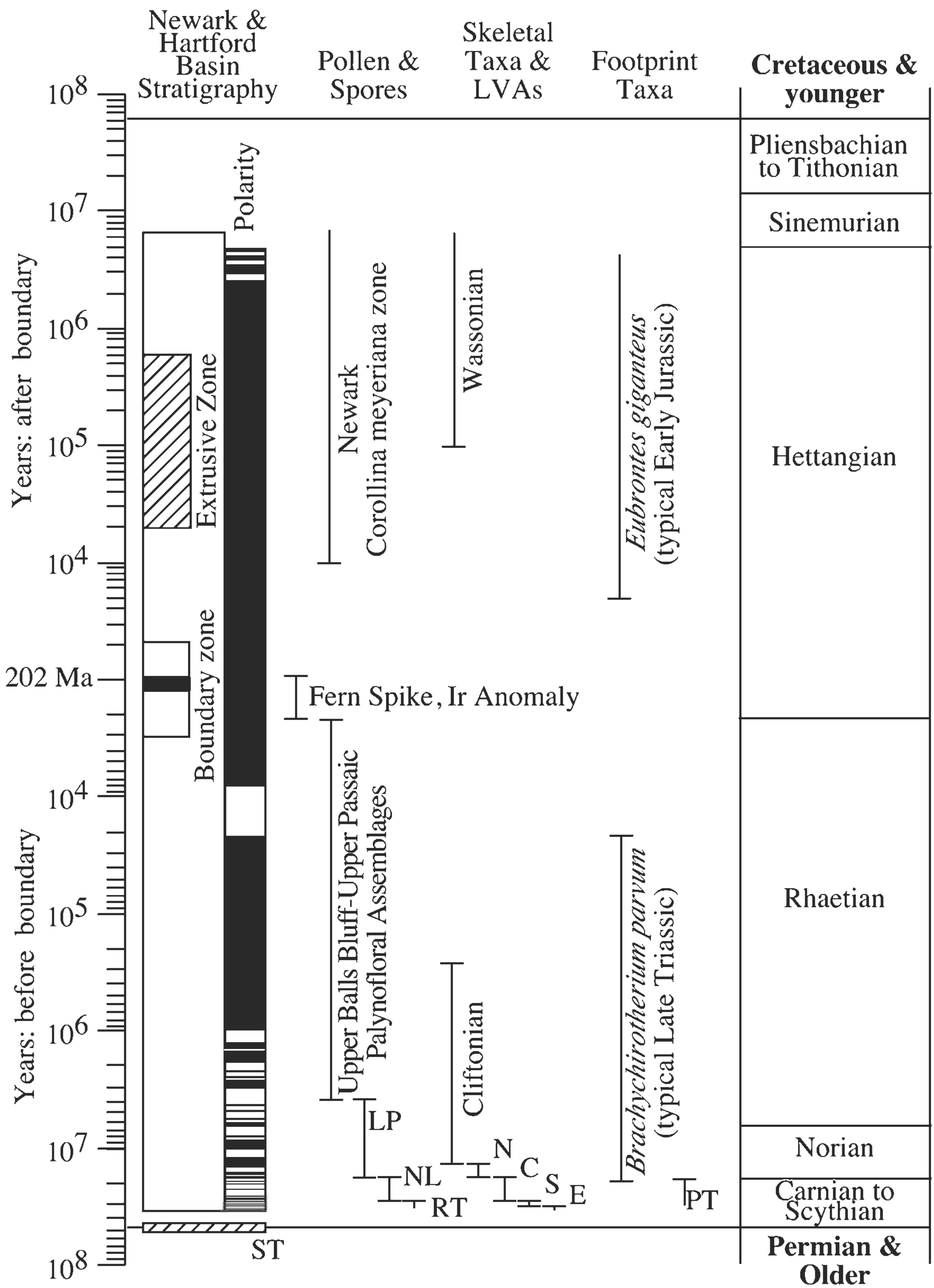


Figure 11. Details of track ranges and Ir anomaly.

Figure 12. Triassic Jurassic Events.



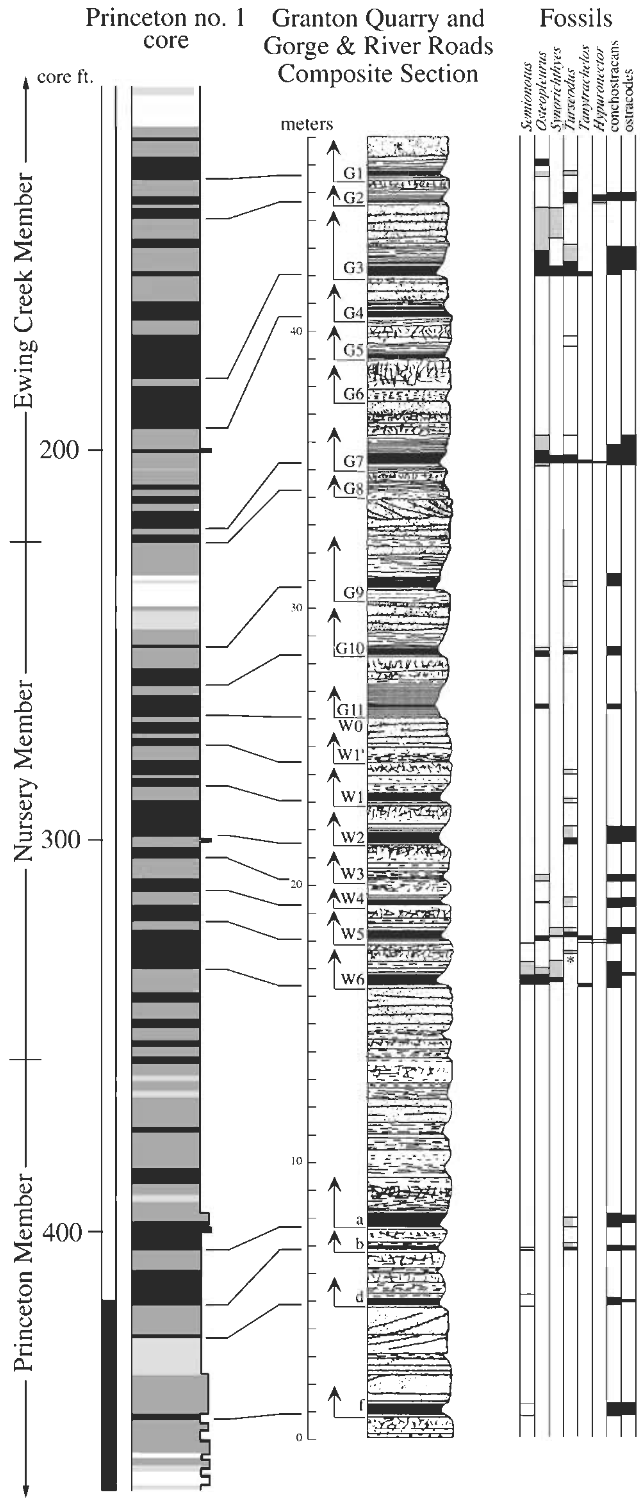

Princeton no. 1 core
Granton Quarry and Gorge & River Roads Composite Section
Fossils
core ft.
Ewing Creek Member
Nursery Member
Princeton Member
200
300
400
meters
40
30
20
10
0
G1
G2
G3
G4
G5
G6
G7
G8
G9
G10
G11
W0
W1'
W1
W2
W3
W4
W5
W6
a
b
d
f
Semionotus
Osteopleurus
Synorichthyes
Turseodus
Tanytrachelos
Hypuronector
conchostracans
ostracodes

Figure 13.

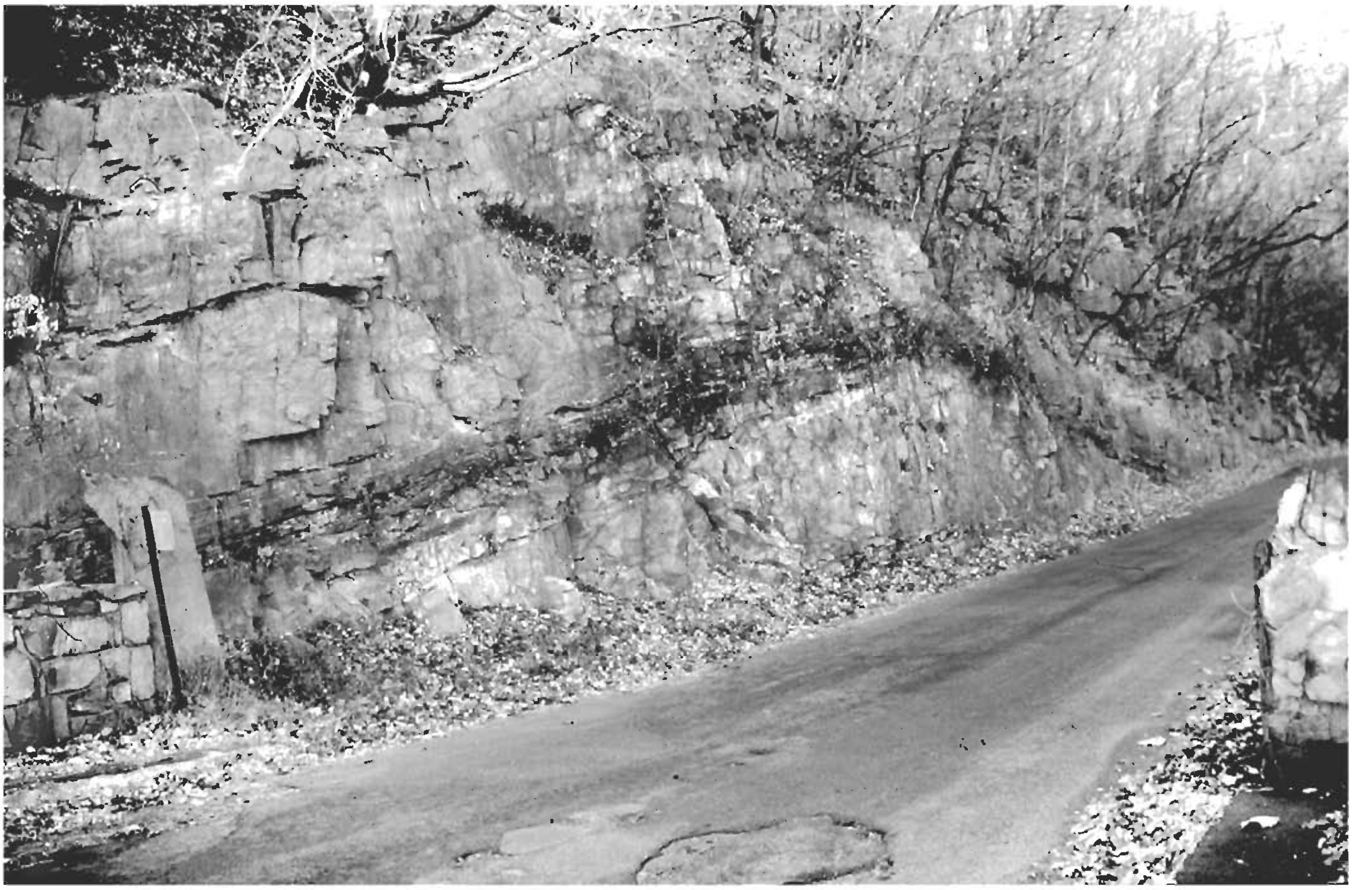


Figure 14

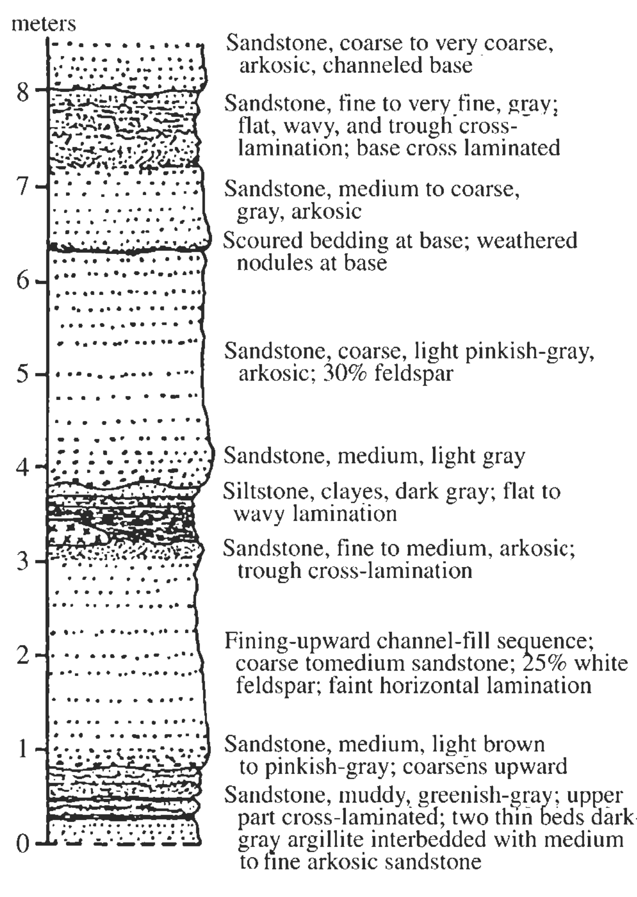


Figure 15

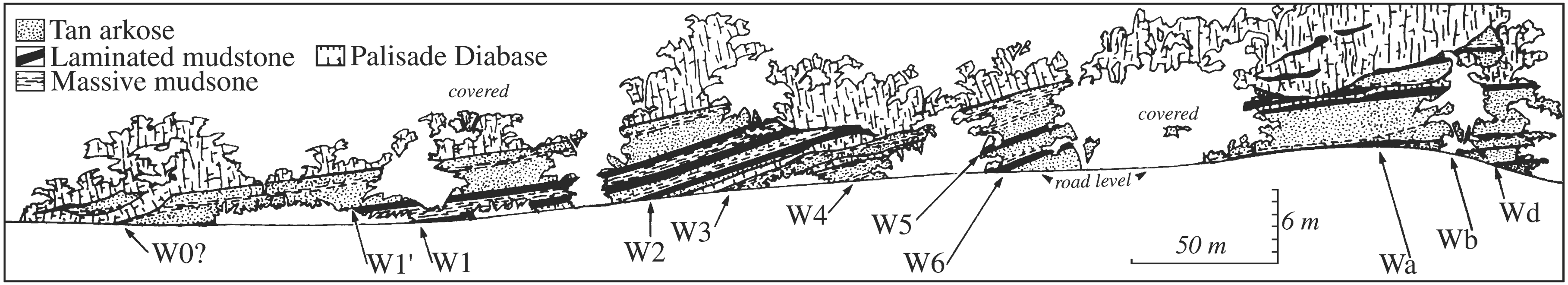


Figure 16

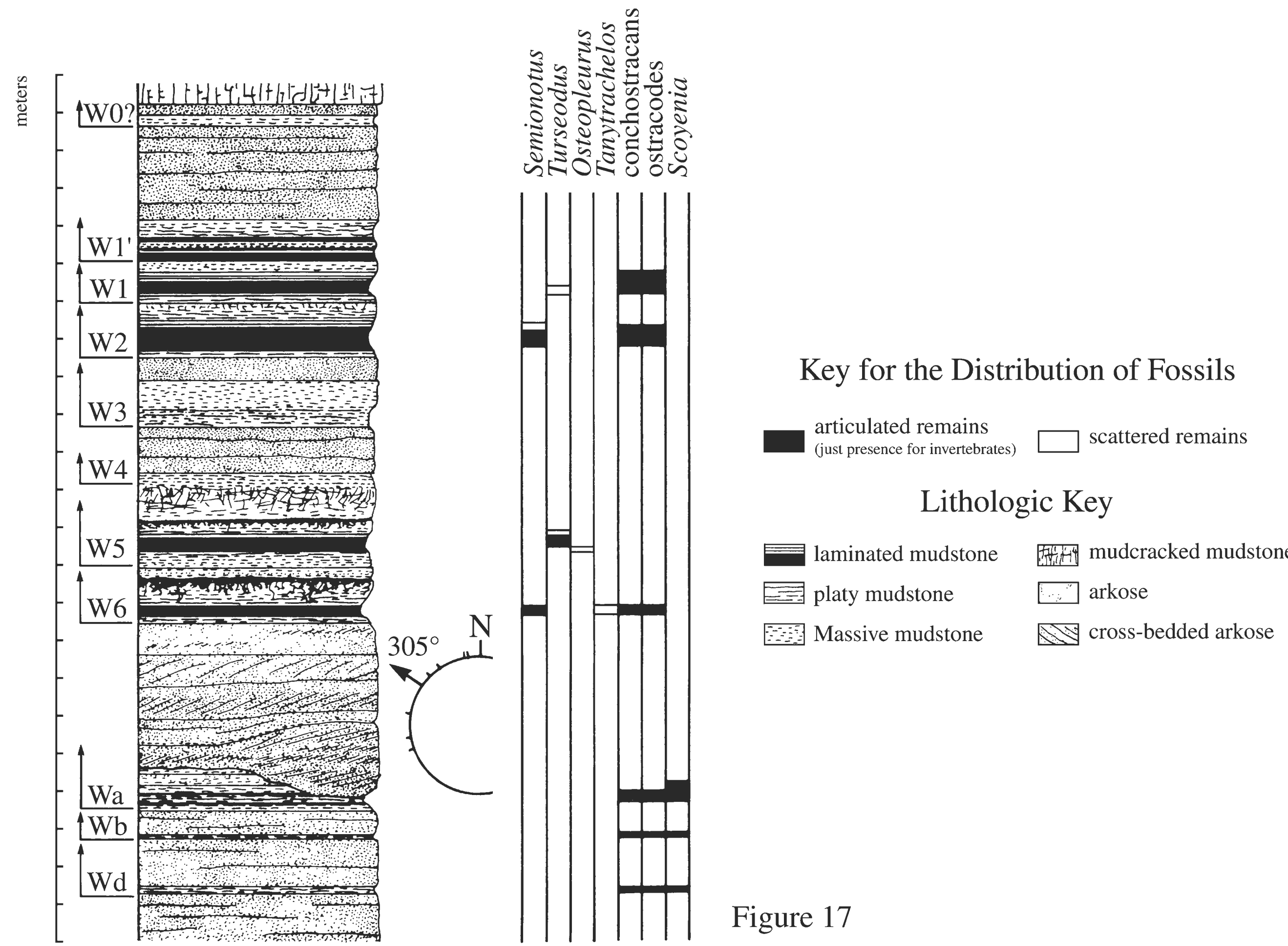
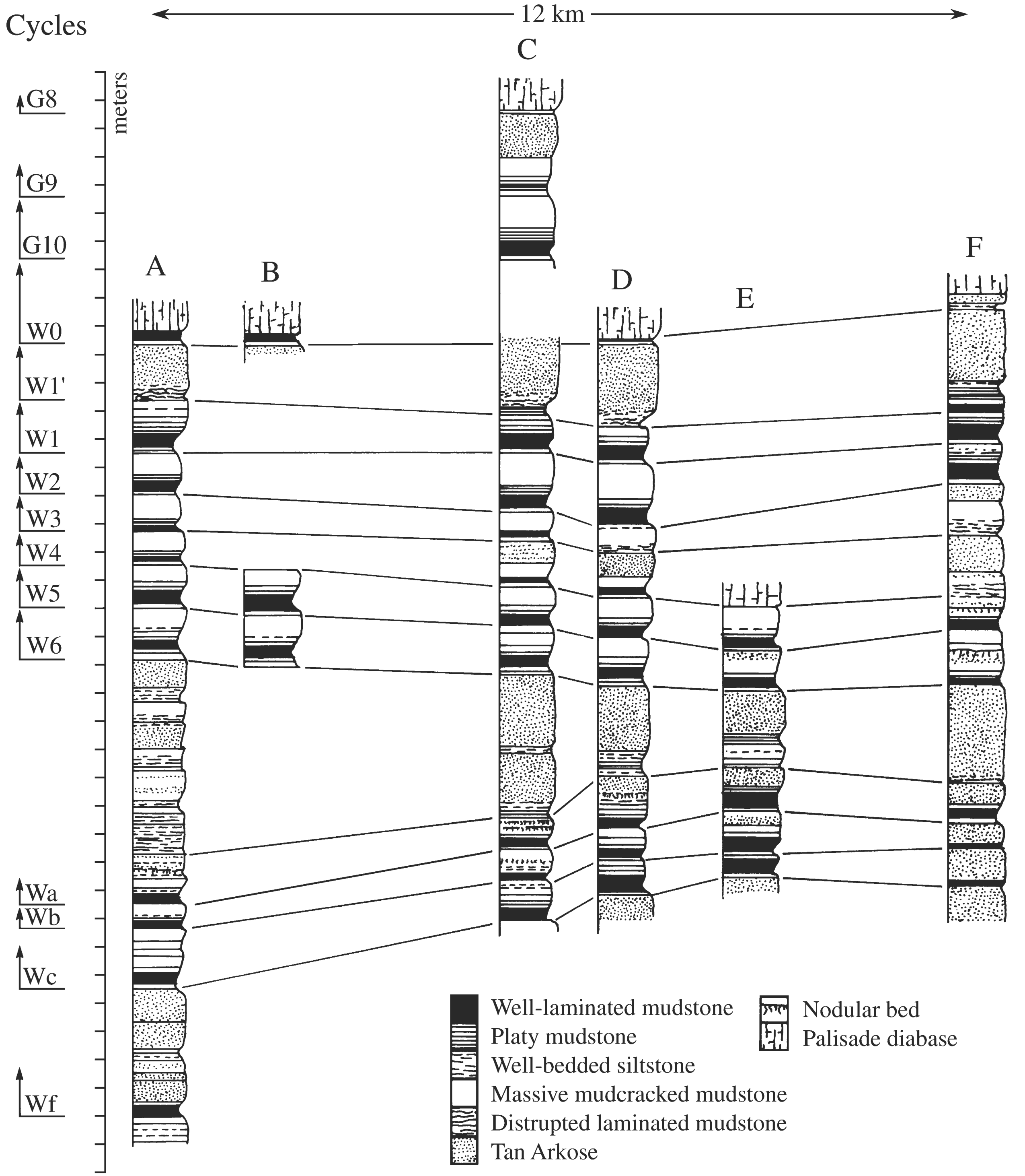


Figure 17


Cycles
12 km
meters
G8
G9
G10
W0
W1'
W1
W2
W3
W4
W5
W6
Wa
Wb
Wc
Wf
A
B
C
D
E
F
Well-laminated mudstone
Platy mudstone
Well-bedded siltstone
Massive mudcracked mudstone
Distrupted laminated mudstone
Tan Arkose
Nodular bed
Palisade diabase

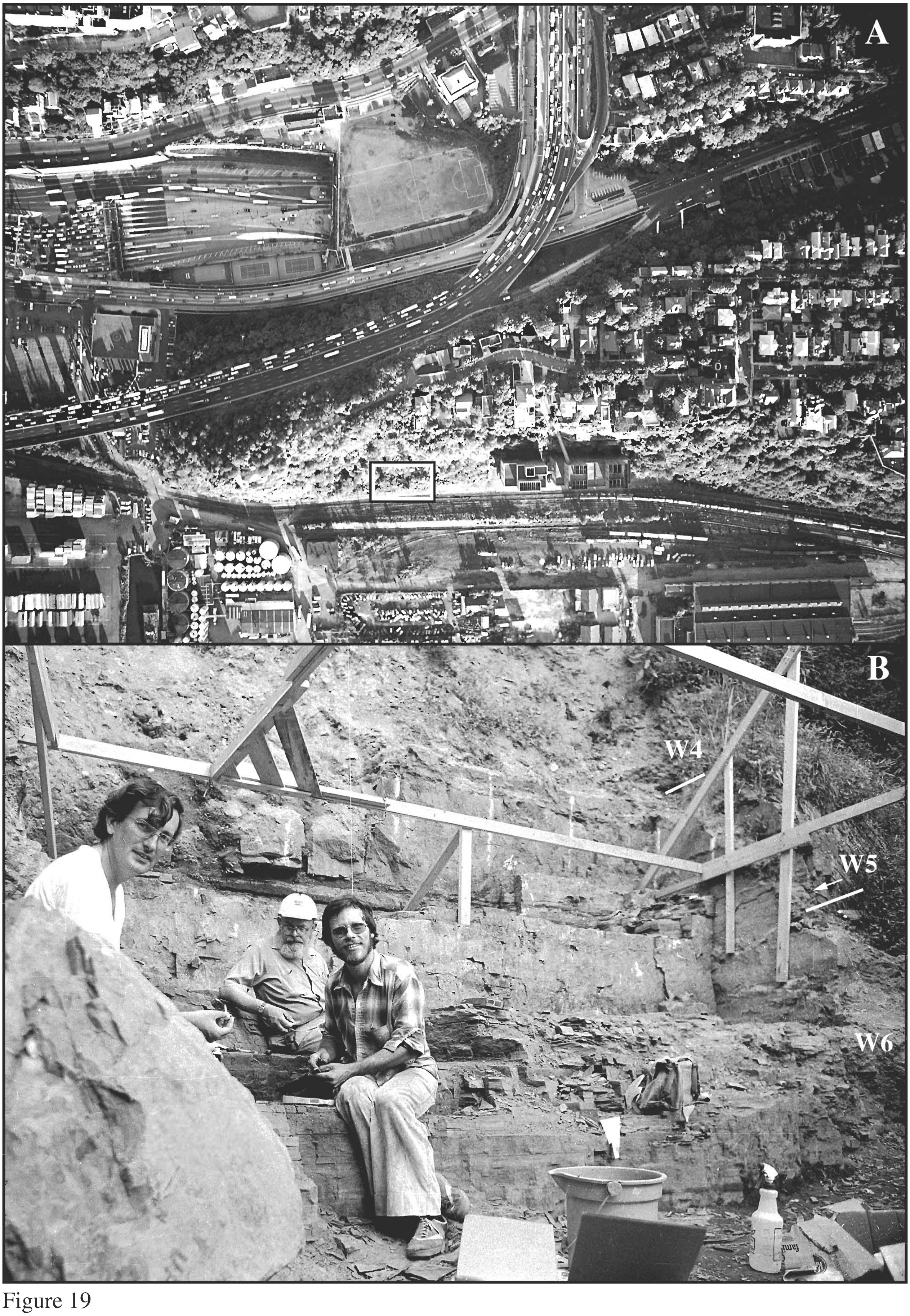
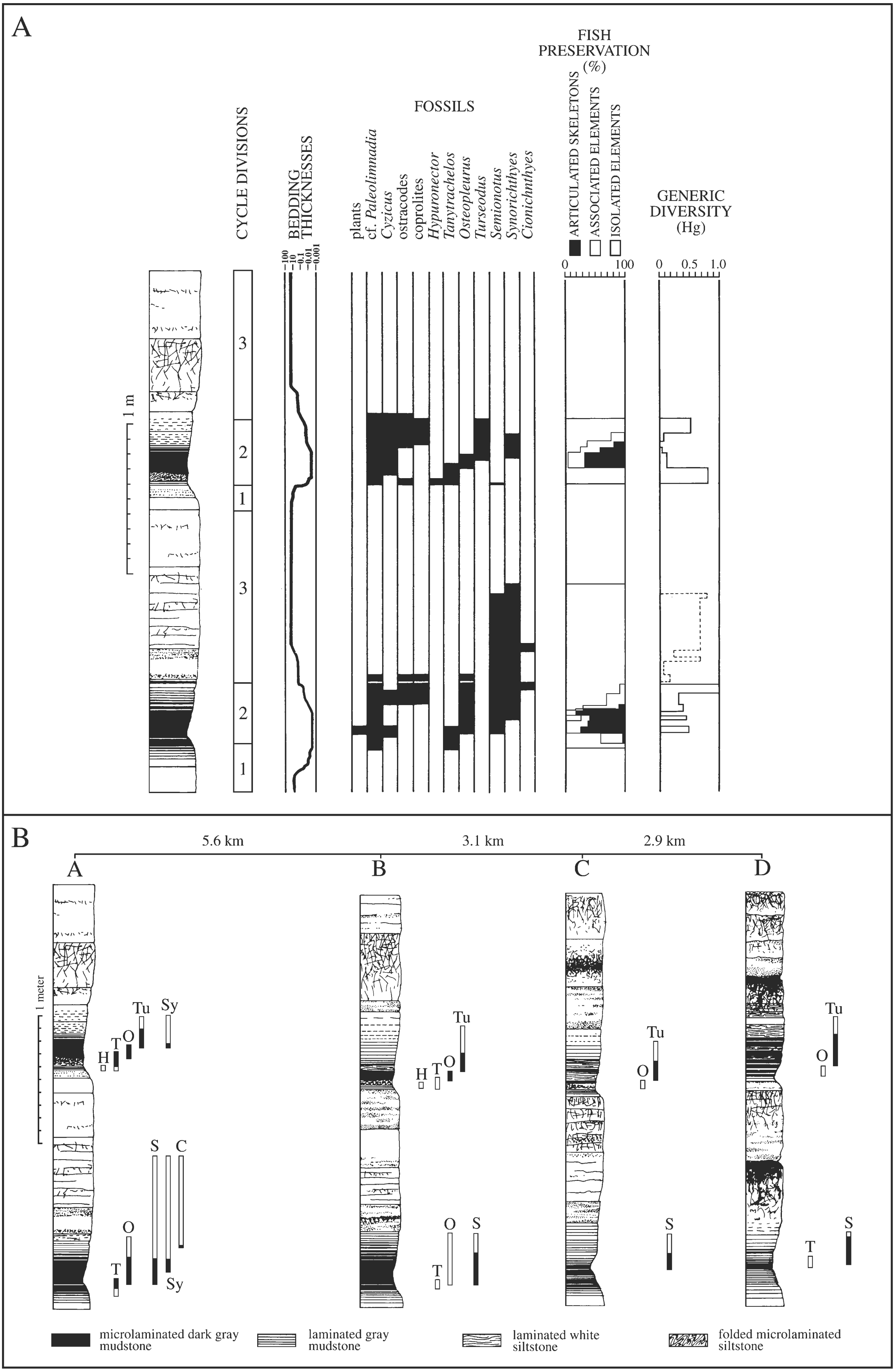


Figure 19

Figure 20



A
CYCLE DIVISIONS
BEDDING THICKNESSES
100
10
1
0.1
0.01
0.001
FOSSILS
plants
cf. Paleolimnadia
Cyzicus
ostracodes
coprolites
Hypuronector
Tanytrachelos
Osteopleurus
Turseodus
Semionotus
Synorichthyes
Cionichthyes
FISH PRESERVATION (%)
ARTICULATED SKELETONS
ASSOCIATED ELEMENTS
ISOLATED ELEMENTS
0
100
GENERIC DIVERSITY (Hg)
0
0.5
1.0
1 m
3
2
1
3
2
1
B
5.6 km
3.1 km
2.9 km
A
B
C
D
1 meter
H
T
O
Tu
Sy
S
C
Sy
microlaminated dark gray mudstone
laminated gray mudstone
laminated white siltstone
folded microlaminated siltstone

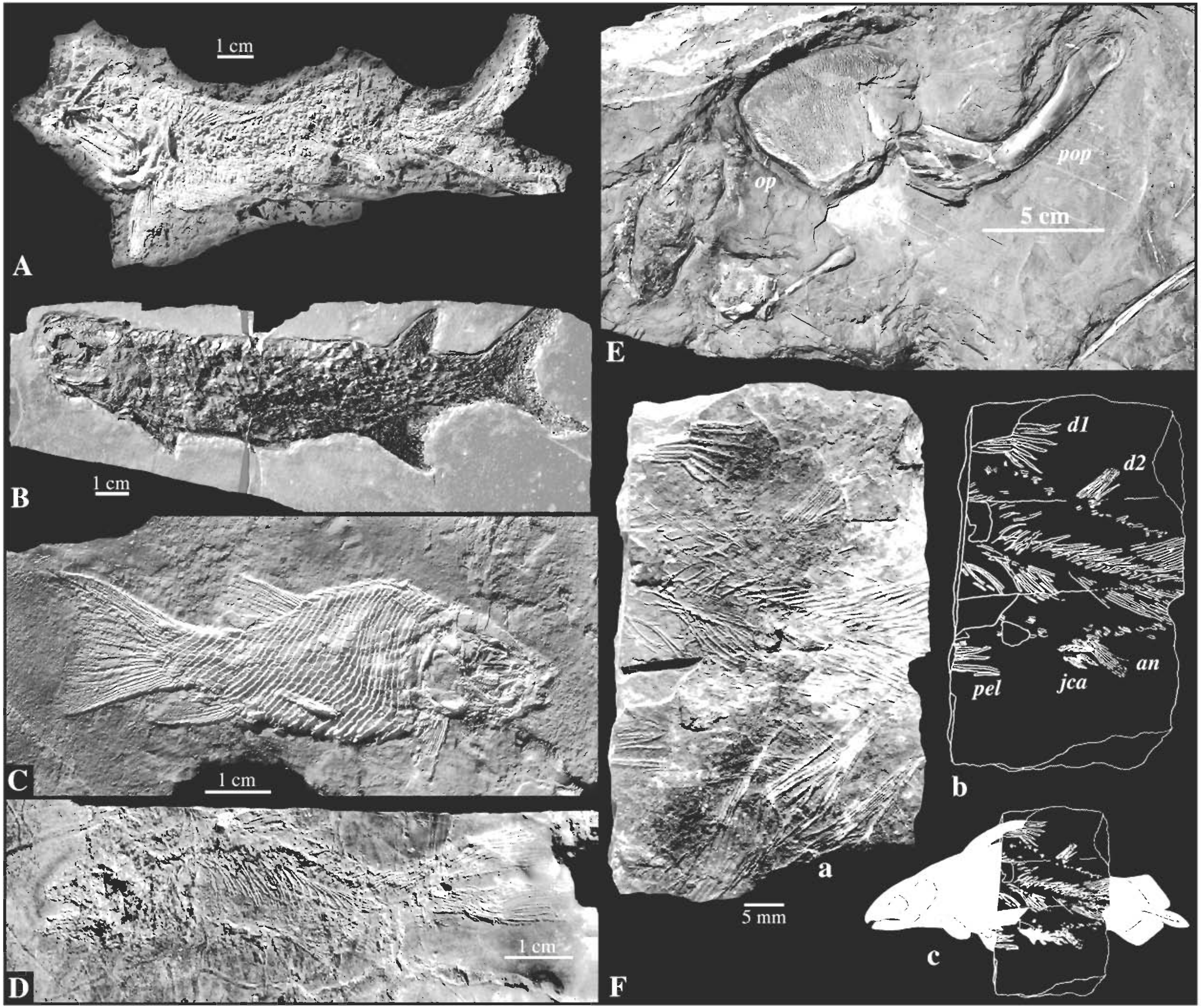


Figure21

Figure 22

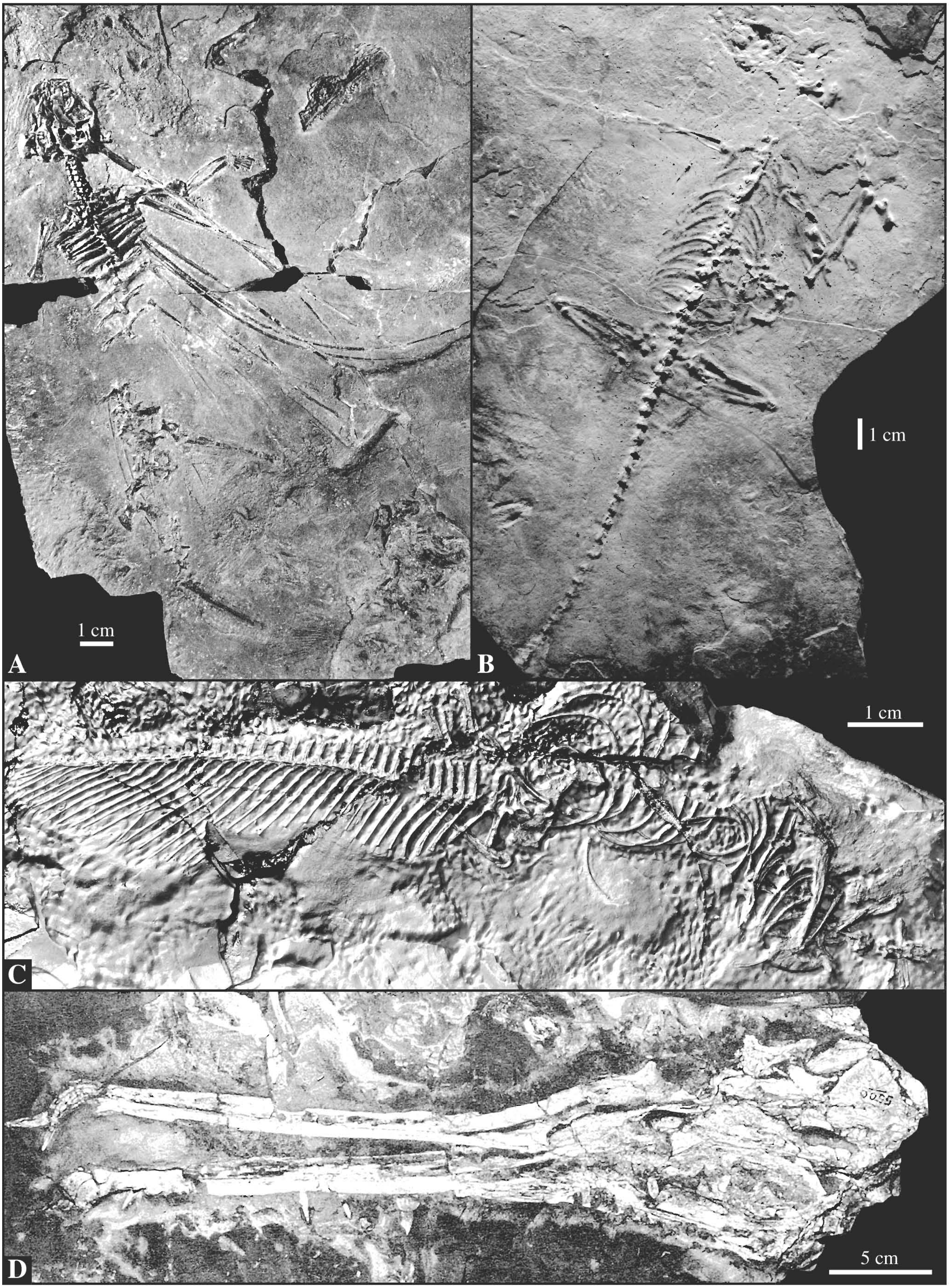


Figure 23

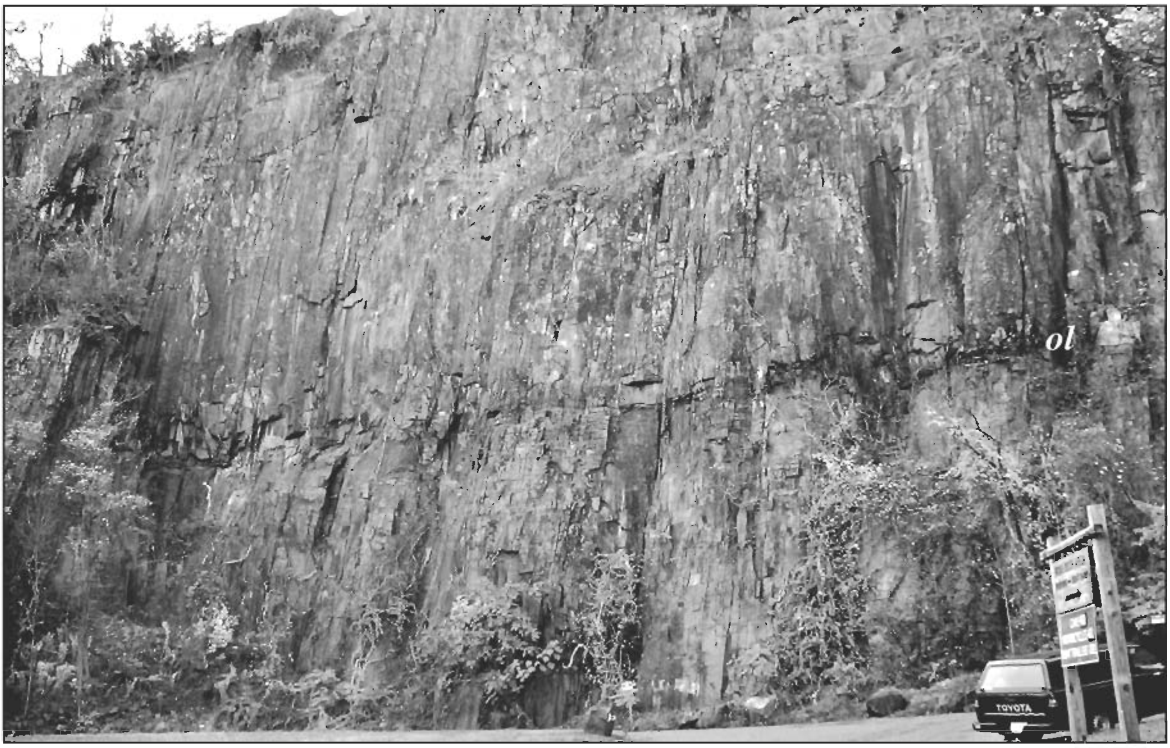


Figure 24

Figure 25

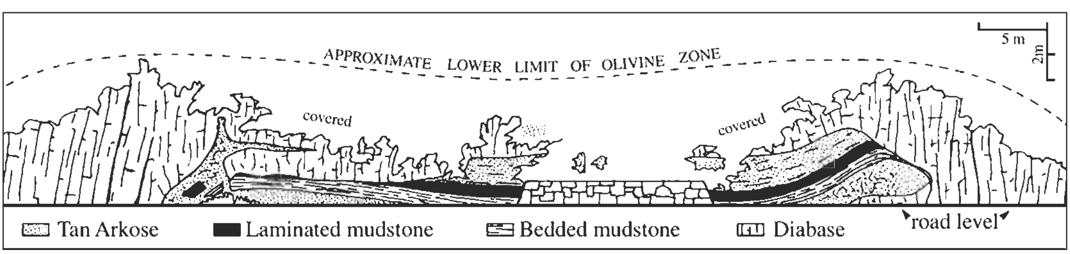


Figure 26

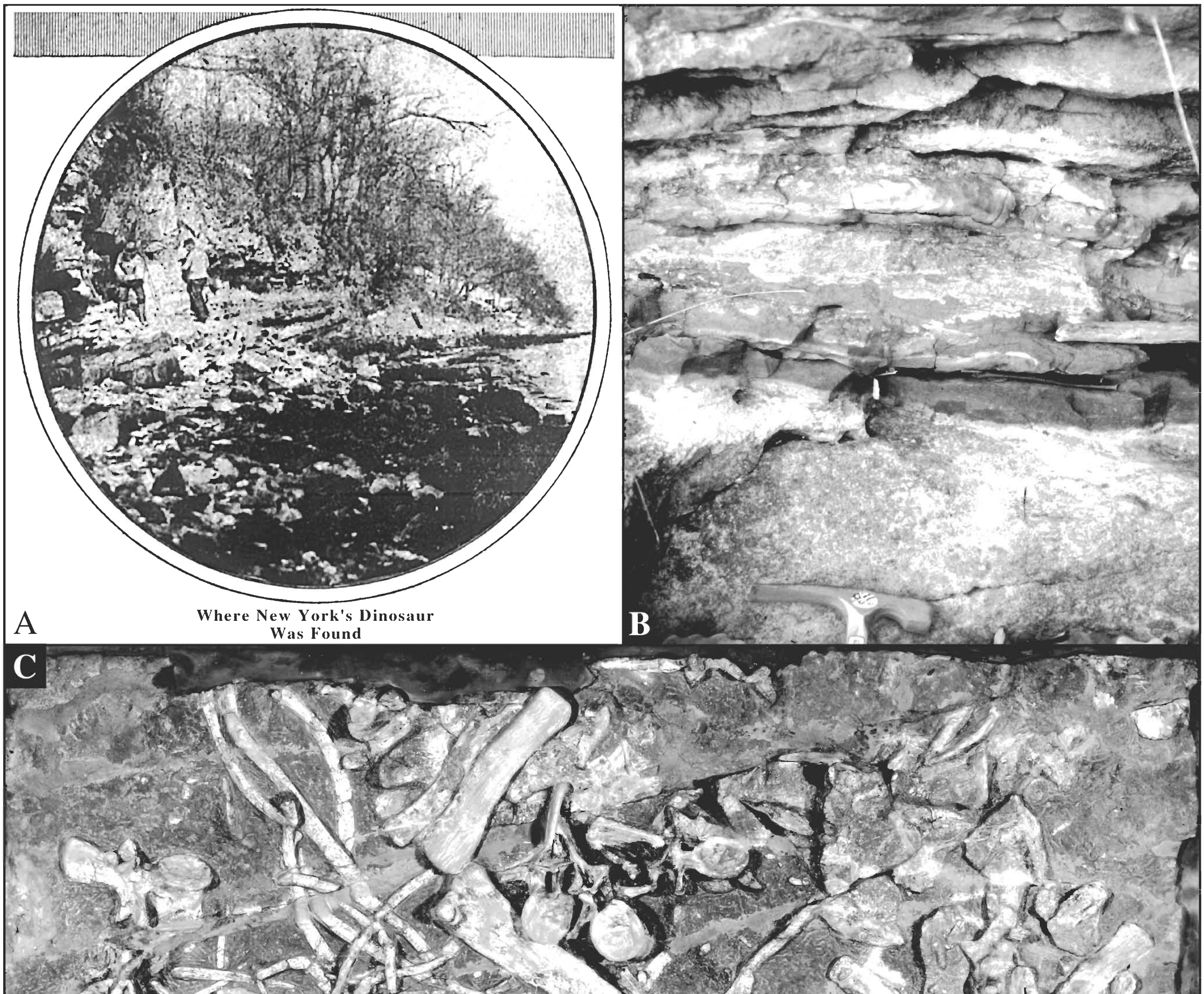


Figure 27

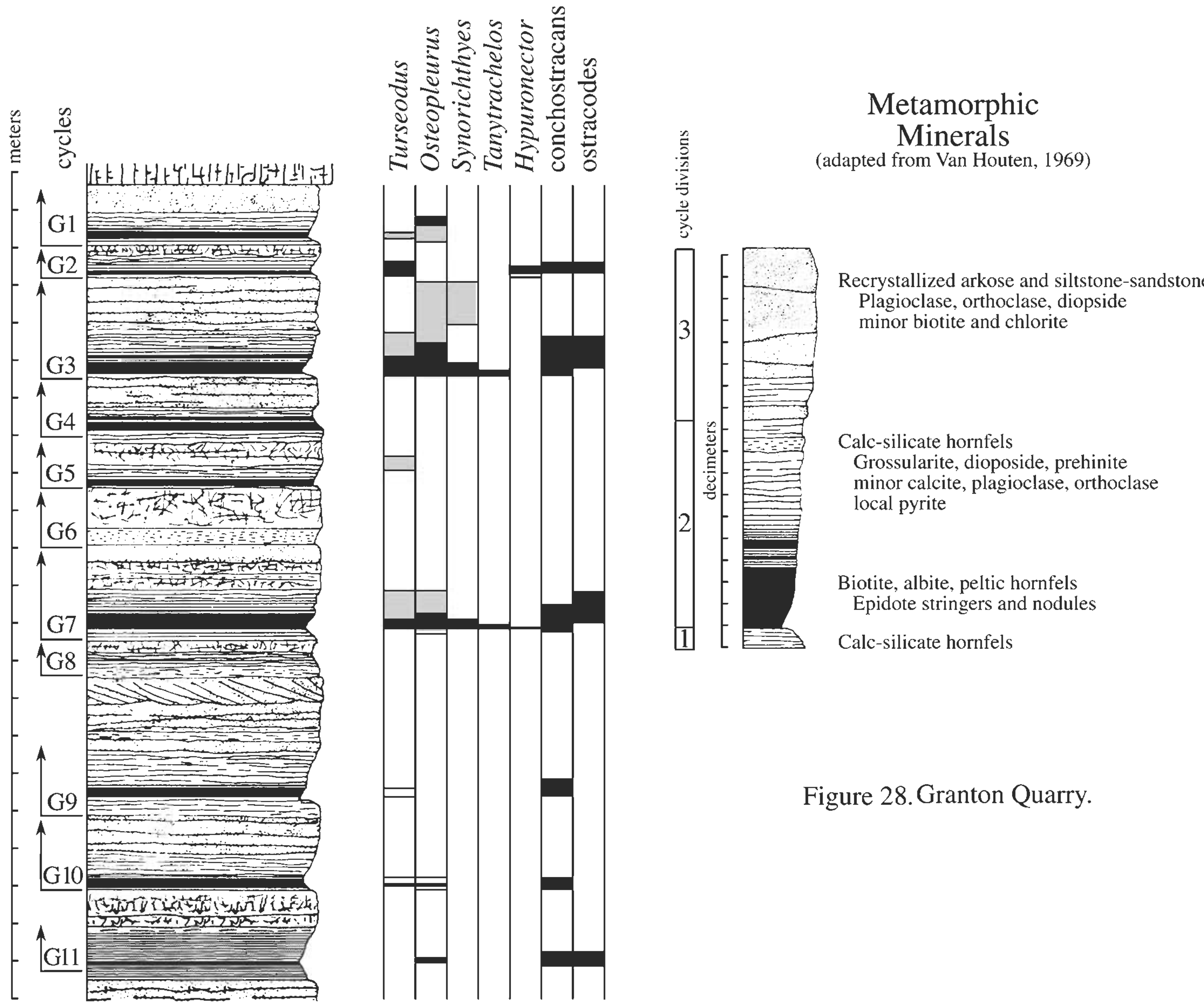


Figure 28. Granton Quarry.

Figure 29. Stop 1.3, Passaic Formation.

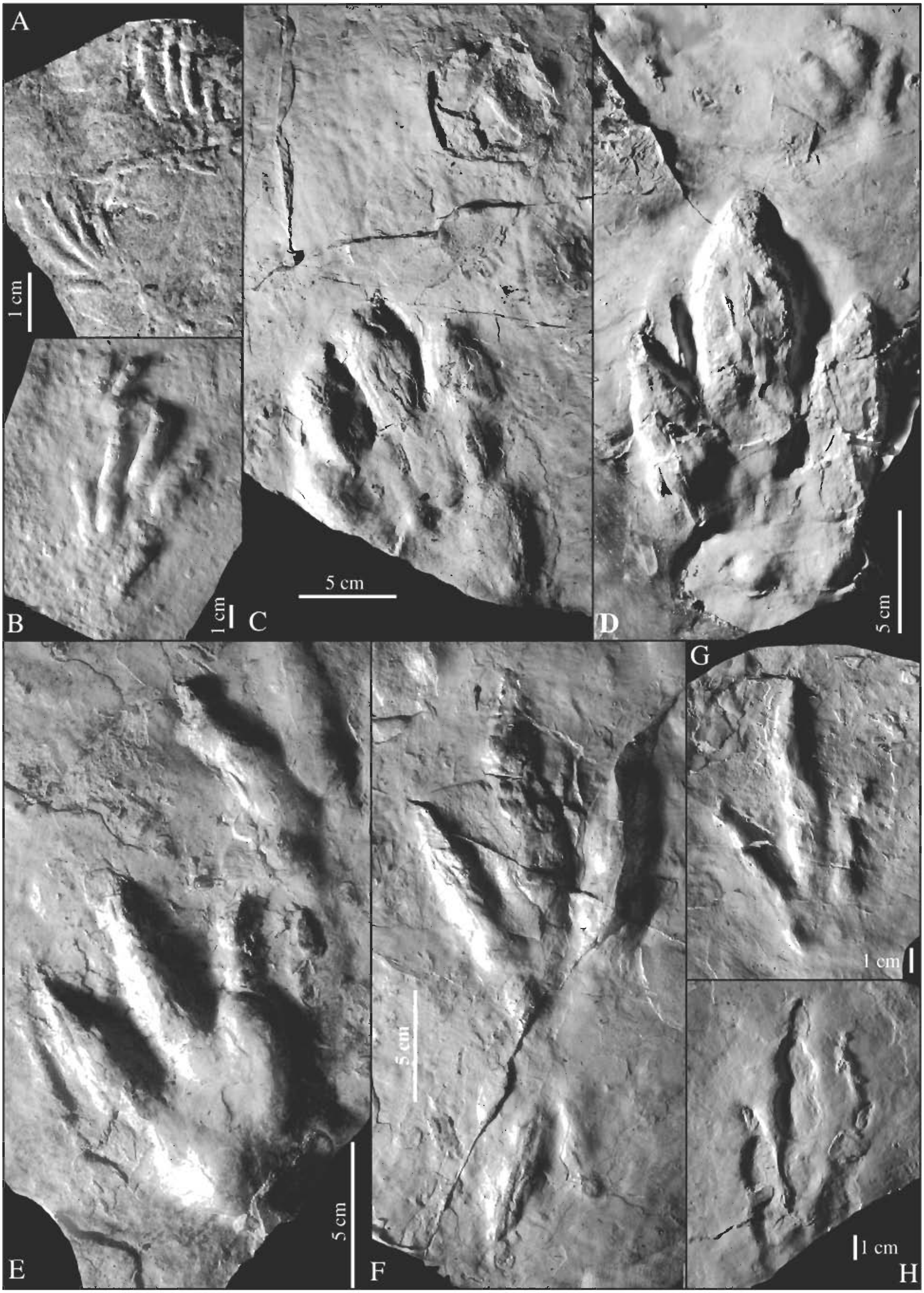
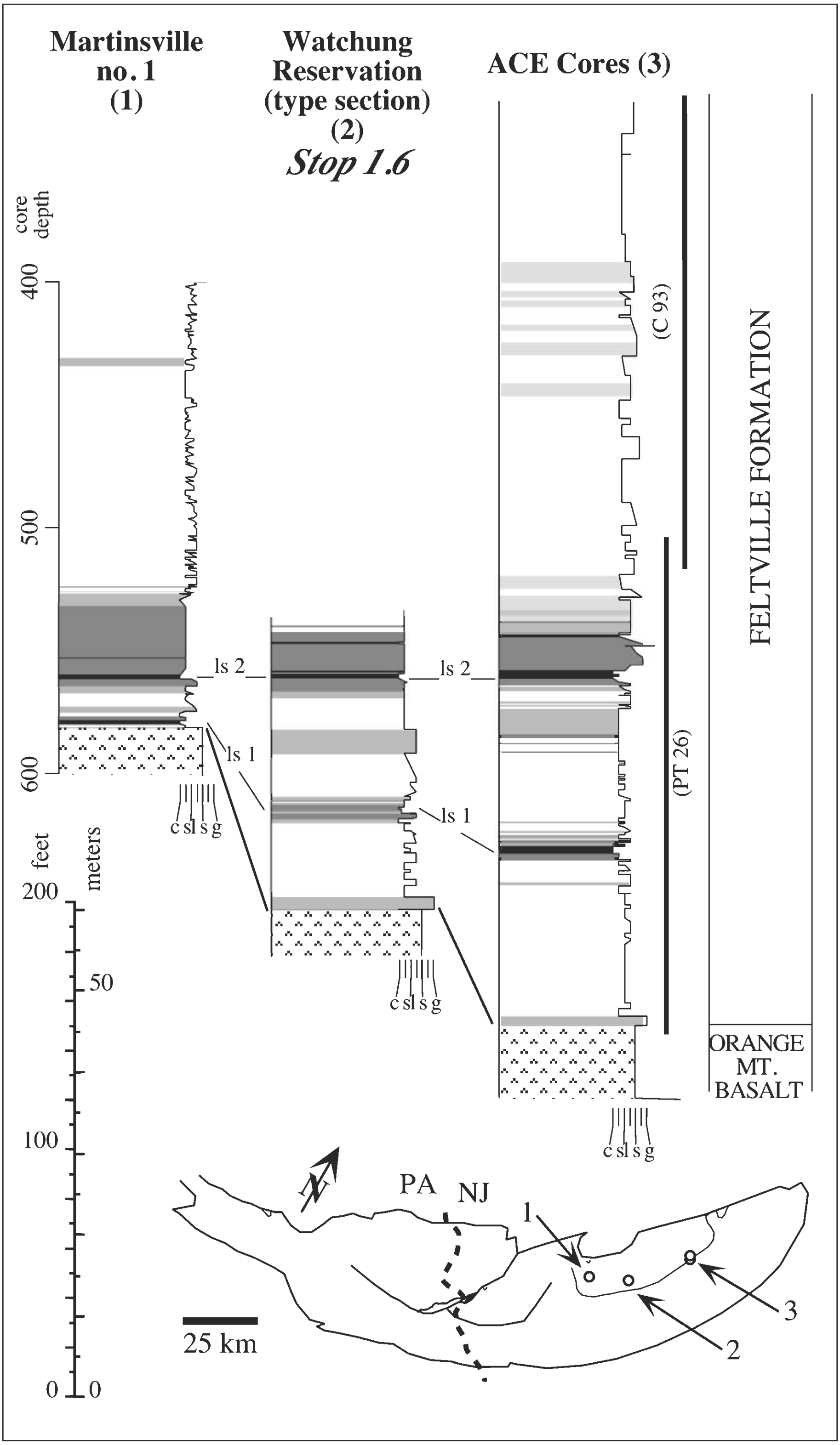


Figure 30



Martinsville no. 1 (1)
Watchung Reservation (type section) (2)
Stop 1.6
ACE Cores (3)
core depth
400
500
600
ls 2
ls 1
c sl s g
feet
meters
200
50
100
0
(C 93)
(PT 26)
FELTVILLE FORMATION
ORANGE MT. BASALT
PA
NJ
N
1
2
3
25 km

Figure 31

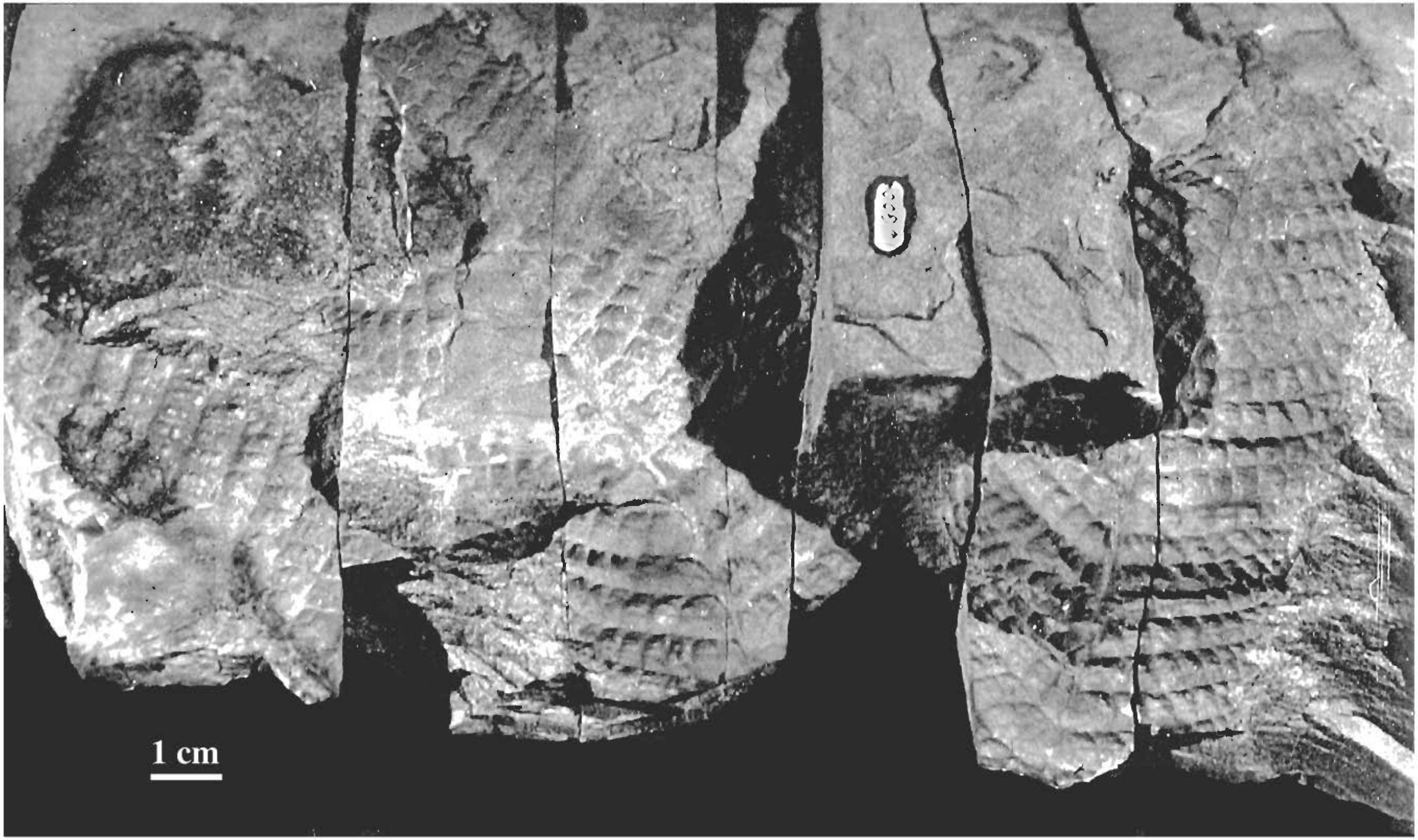


Figure 32

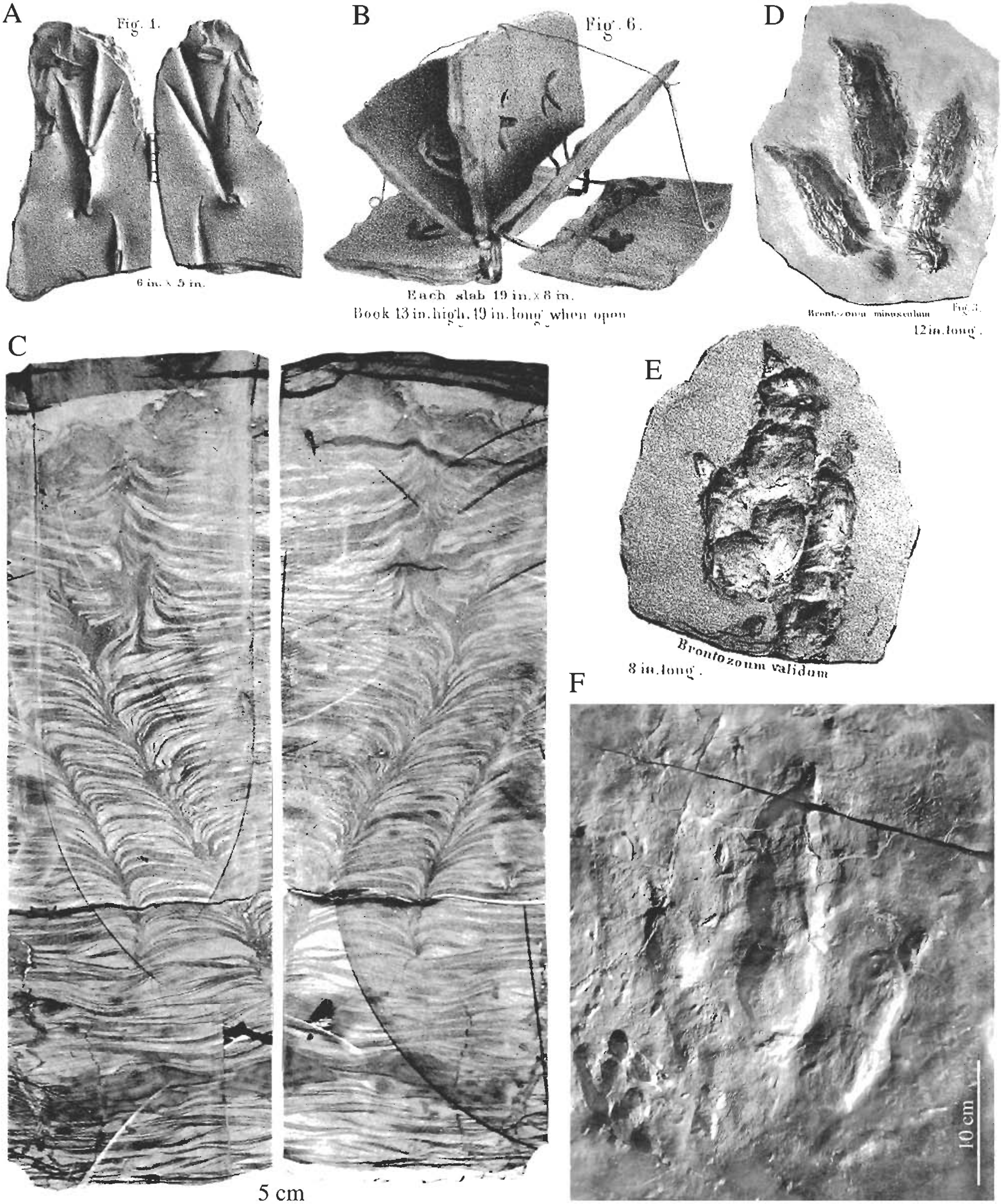
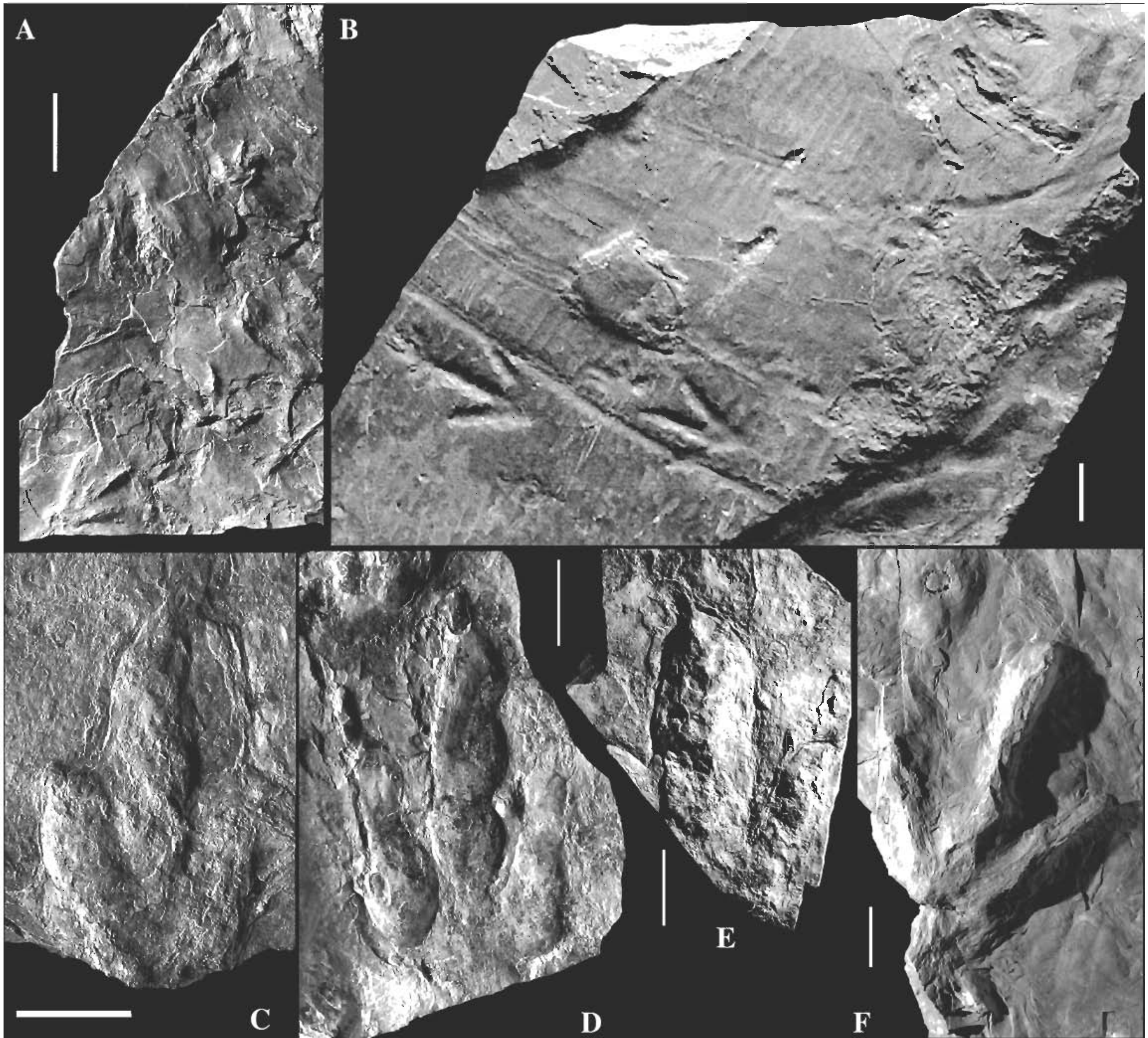

A
Fig. 1.
6 in. x 5 in.
B
Fig. 6.
Each slab 19 in. x 8 in.
Book 13 in. high, 19 in. long when open
D
Brontozoum minusculum
Fig. 3.
12 in. long.
C
E
Brontozoum validum
8 in. long.
F
5 cm
10 cm

Figure 33

Figure 34



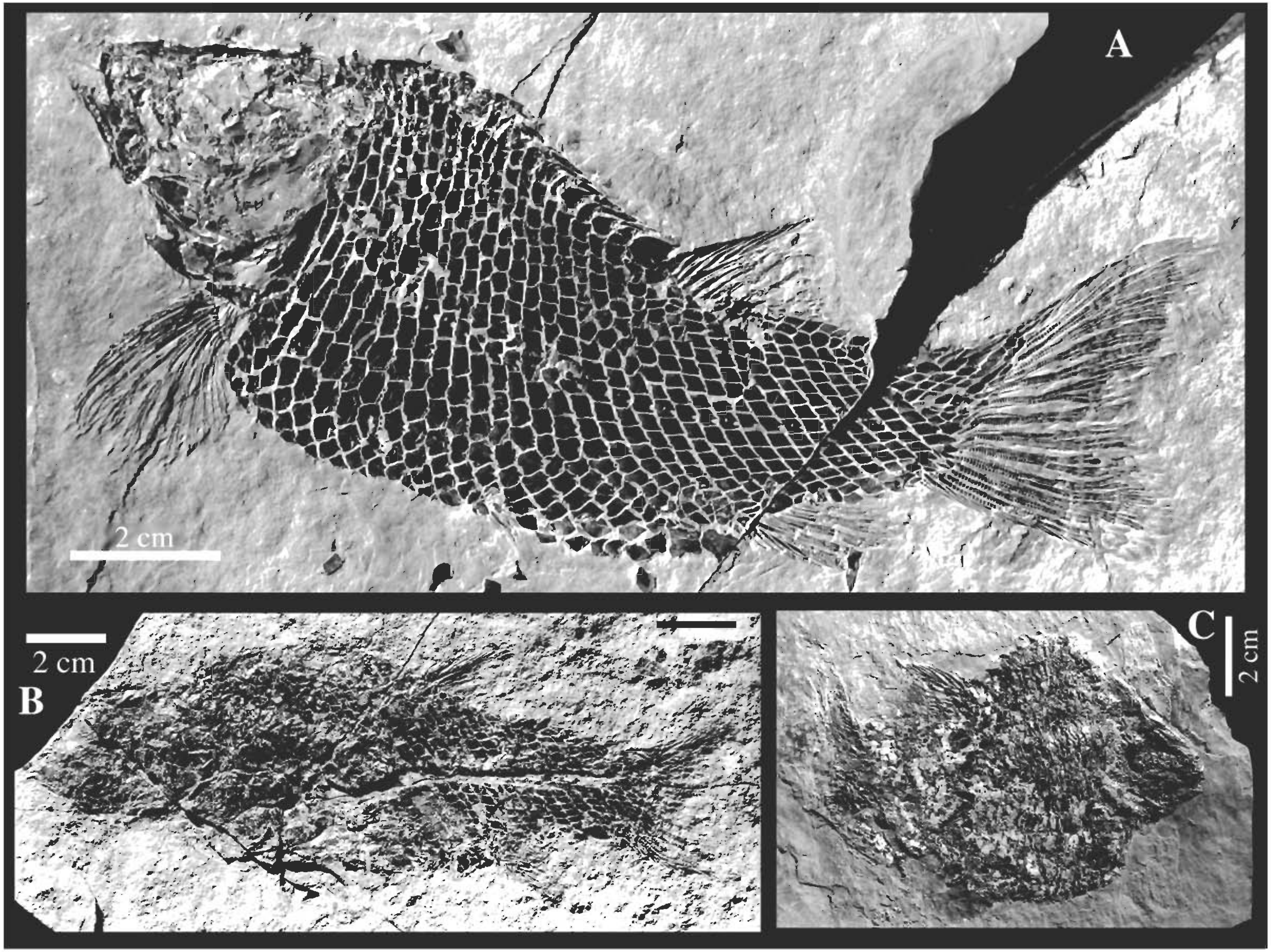


Figure 35. Feltville Fm. semionotids.

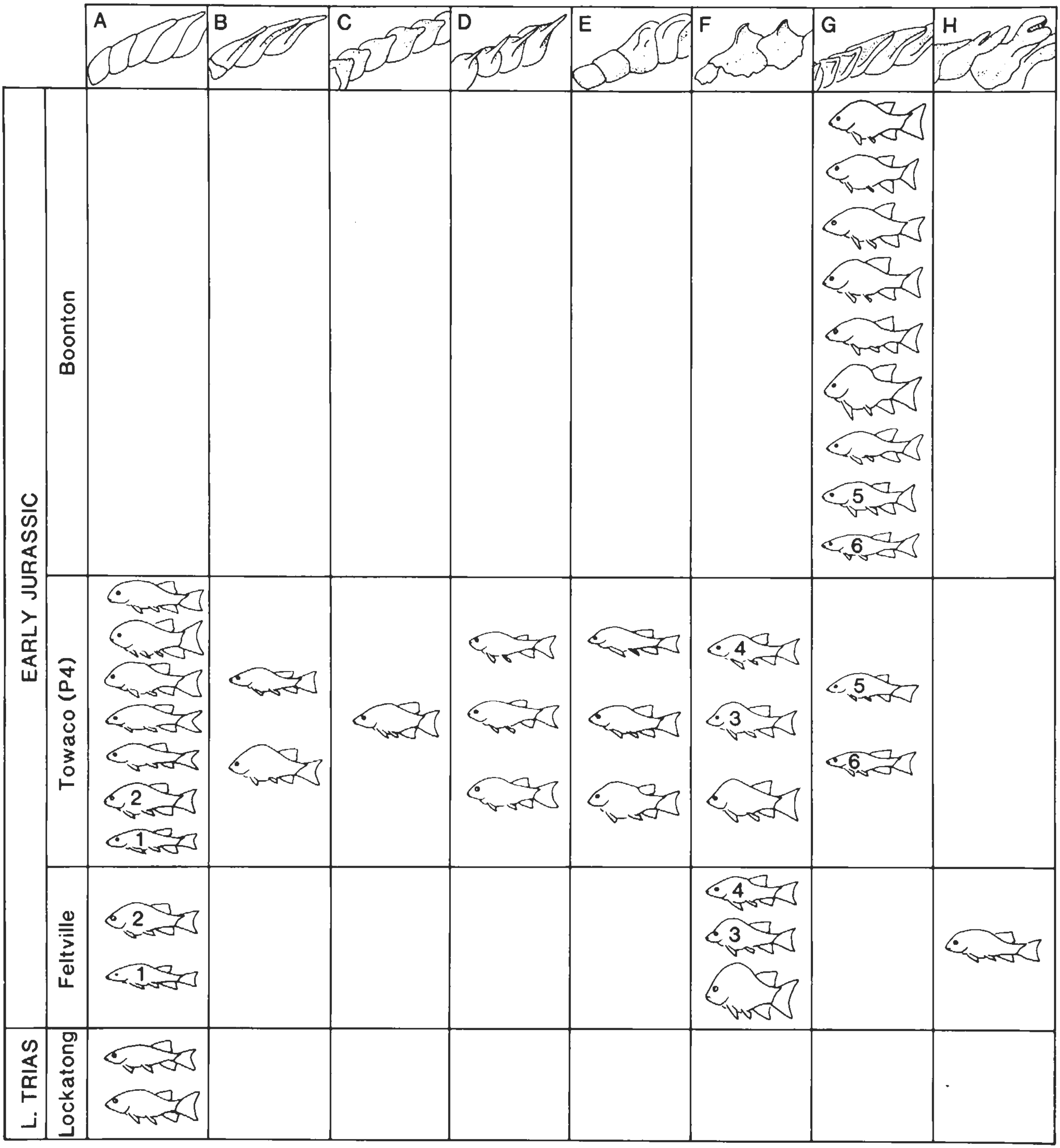

A
B
C
D
E
F
G
H
EARLY JURASSIC
L. TRIAS
Boonton
Towaco (P4)
Feltville
Lockatong
1
2
3
4
5
6

Figure 36

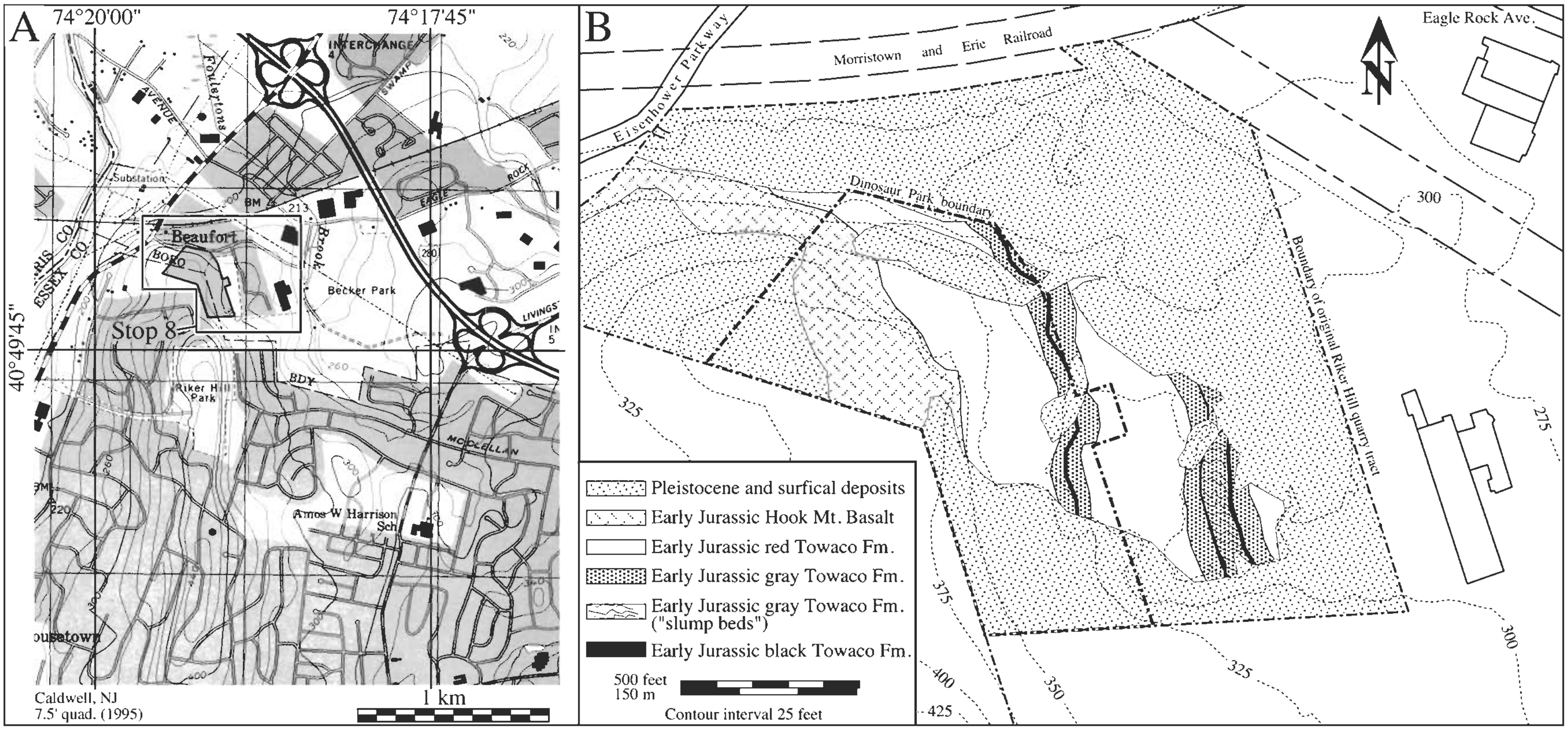
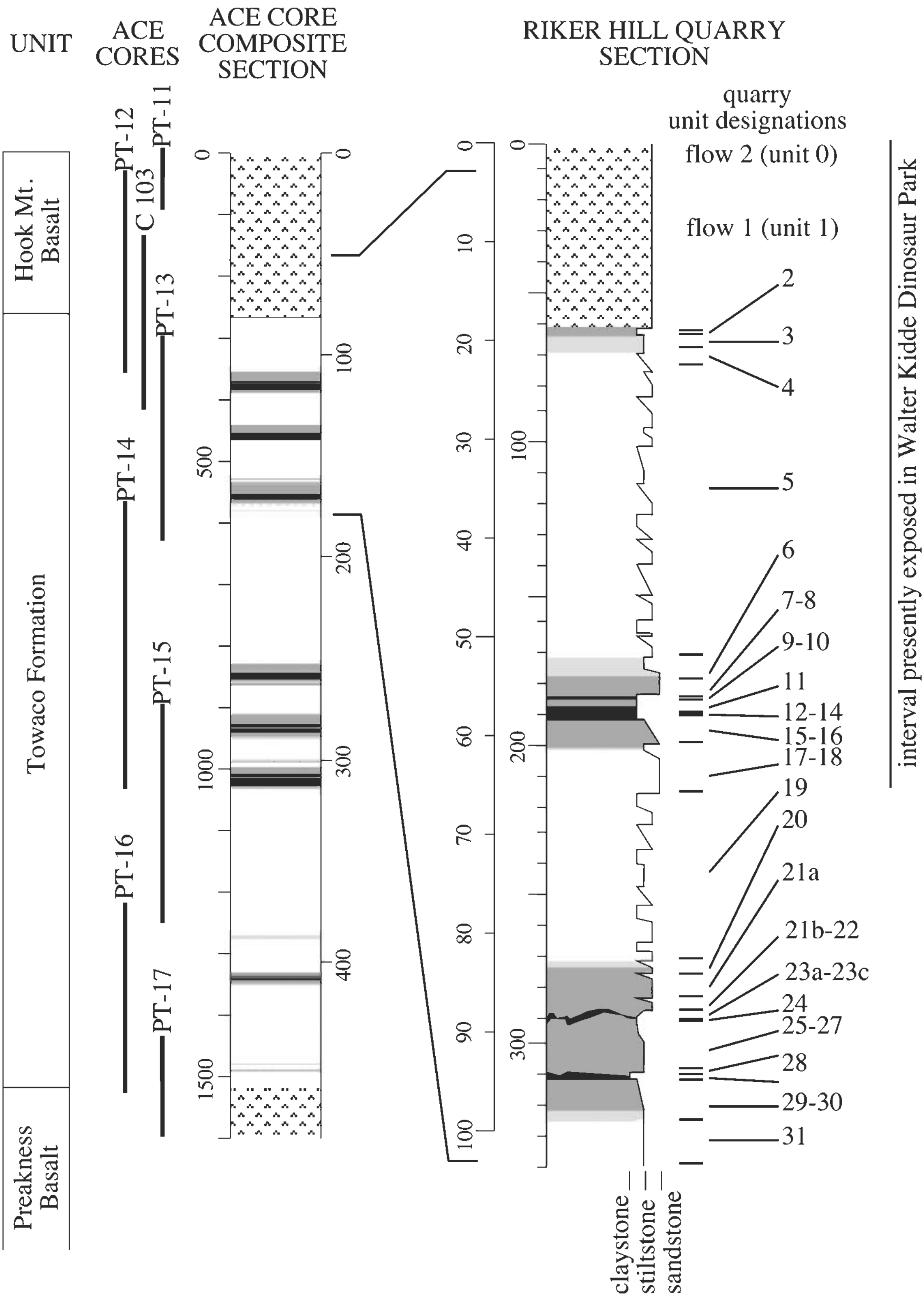

A
74°20'00"
74°17'45"
40°49'45"
INTERCHANGE 4
Foulertons
AVENUE
Substation
Beaufort
BORO
Stop 8
Brook
Becker Park
EAGLE
ROCK
Riker Hill Park
BDY
MCCLELLAN
Amos W Harrison Sch
ESSEX CO
Caldwell, NJ
7.5' quad. (1995)
1 km
B
Eisenhower Parkway
Morristown and Erie Railroad
Eagle Rock Ave.
Dinosaur Park boundary
Boundary of original Riker Hill quarry tract
300
275
325
350
375
400
425
Pleistocene and surfical deposits
Early Jurassic Hook Mt. Basalt
Early Jurassic red Towaco Fm.
Early Jurassic gray Towaco Fm.
Early Jurassic gray Towaco Fm. ("slump beds")
Early Jurassic black Towaco Fm.
500 feet
150 m
Contour interval 25 feet

Figure 37

Figure 38

Figure 39


UNIT
ACE CORES
ACE CORE COMPOSITE SECTION
RIKER HILL QUARRY SECTION
Hook Mt. Basalt
Towaco Formation
Preakness Basalt
PT-11
PT-12
C 103
PT-13
PT-14
PT-15
PT-16
PT-17
0
500
1000
1500
100
200
300
400
10
20
30
40
50
60
70
80
90
quarry unit designations
flow 2 (unit 0)
flow 1 (unit 1)
2
3
4
5
6
7-8
9-10
11
12-14
15-16
17-18
19
20
21a
21b-22
23a-23c
24
25-27
28
29-30
31
interval presently exposed in Walter Kidde Dinosaur Park
claystone
stiltstone
sandstone

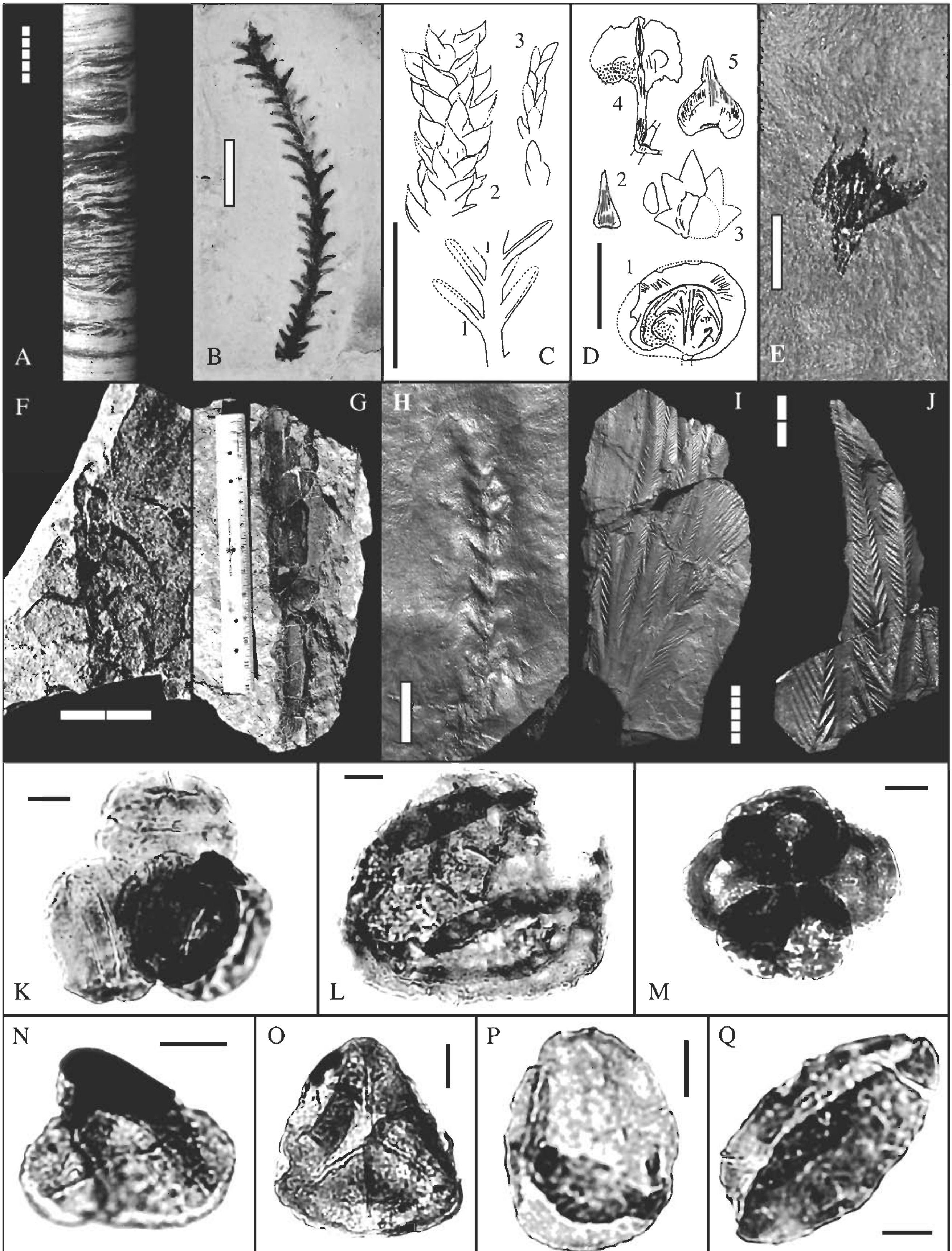


Figure 40

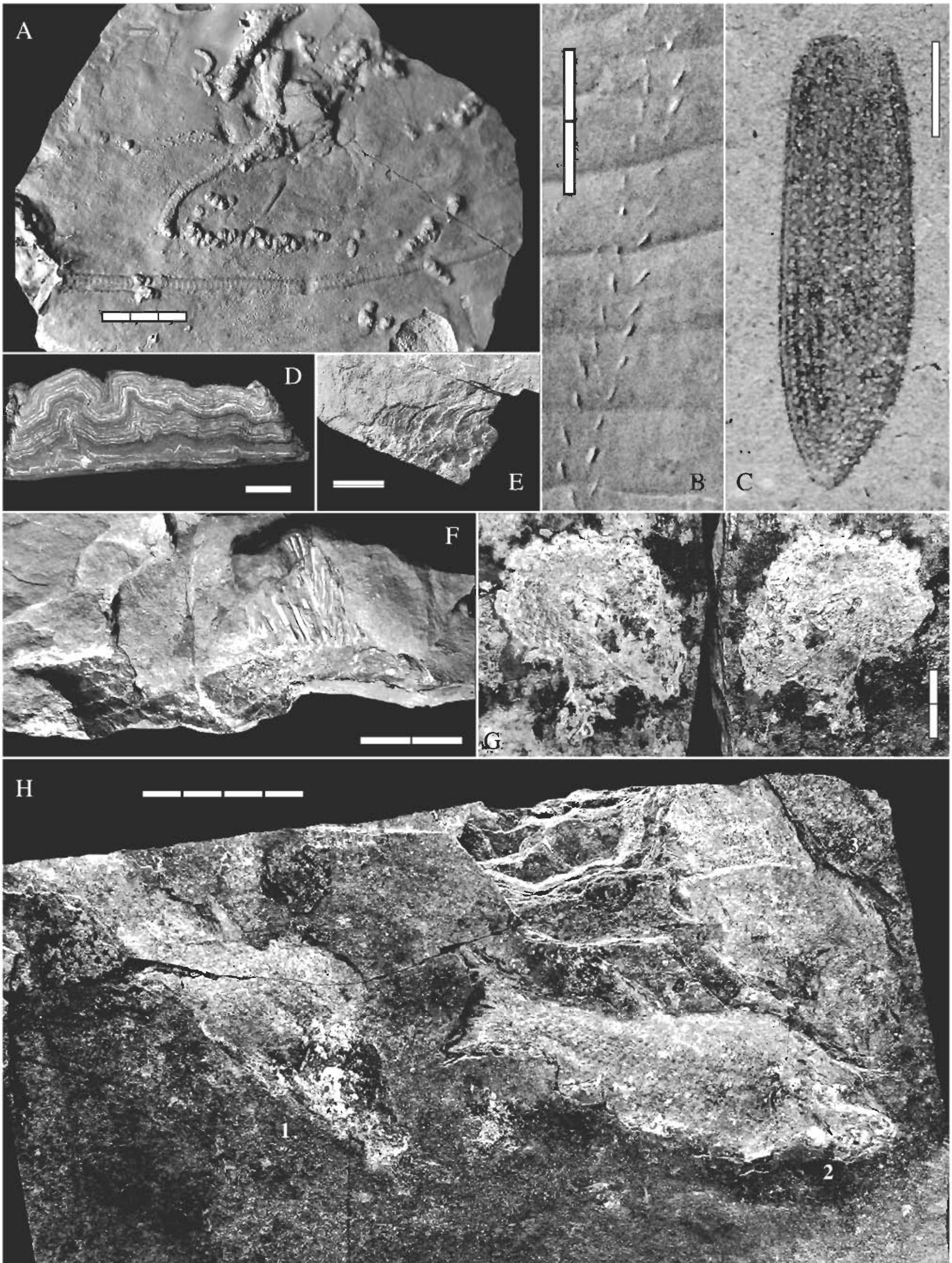


Figure 41

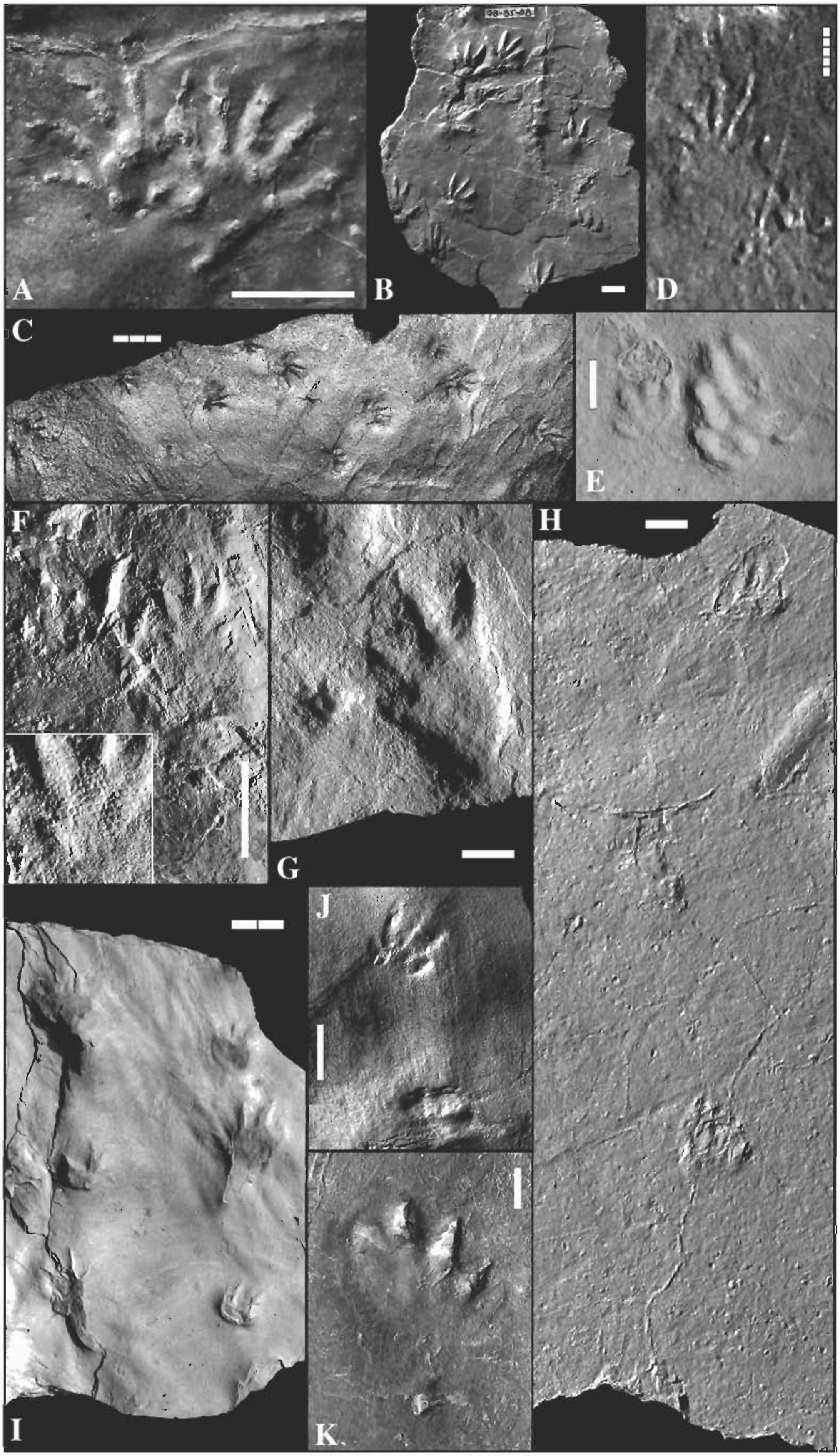


Figure 42

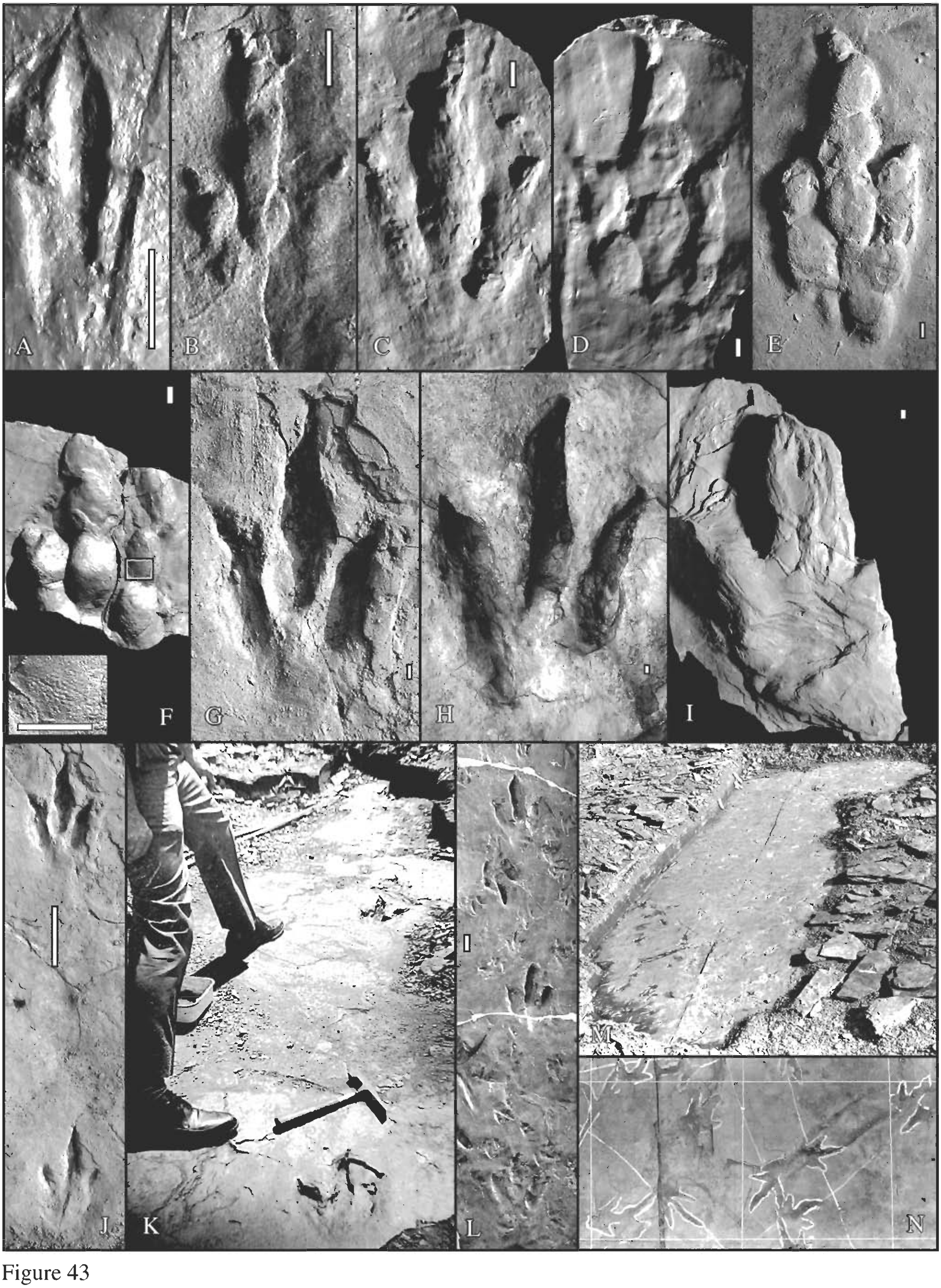


Figure 43

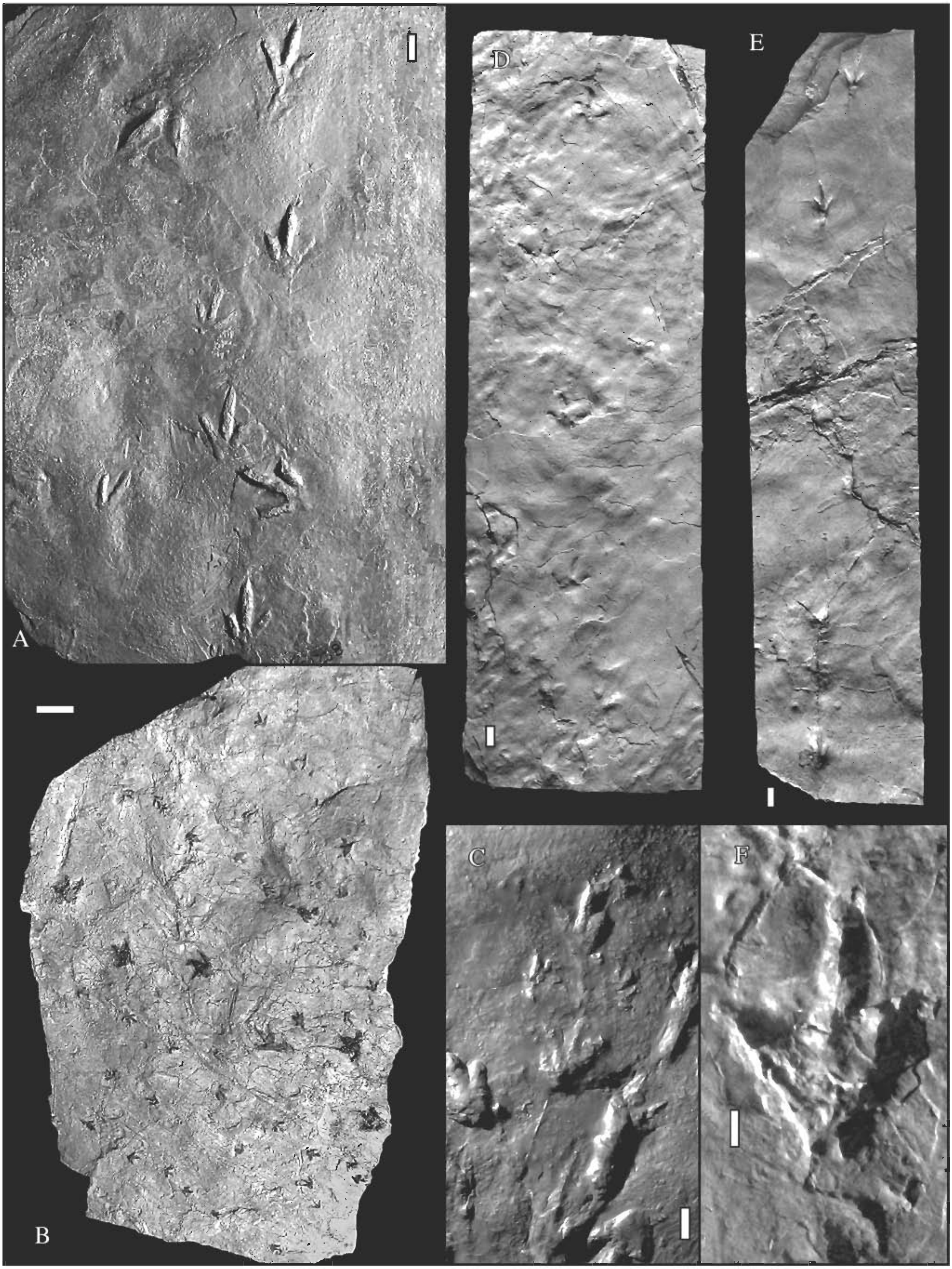


Figure 44

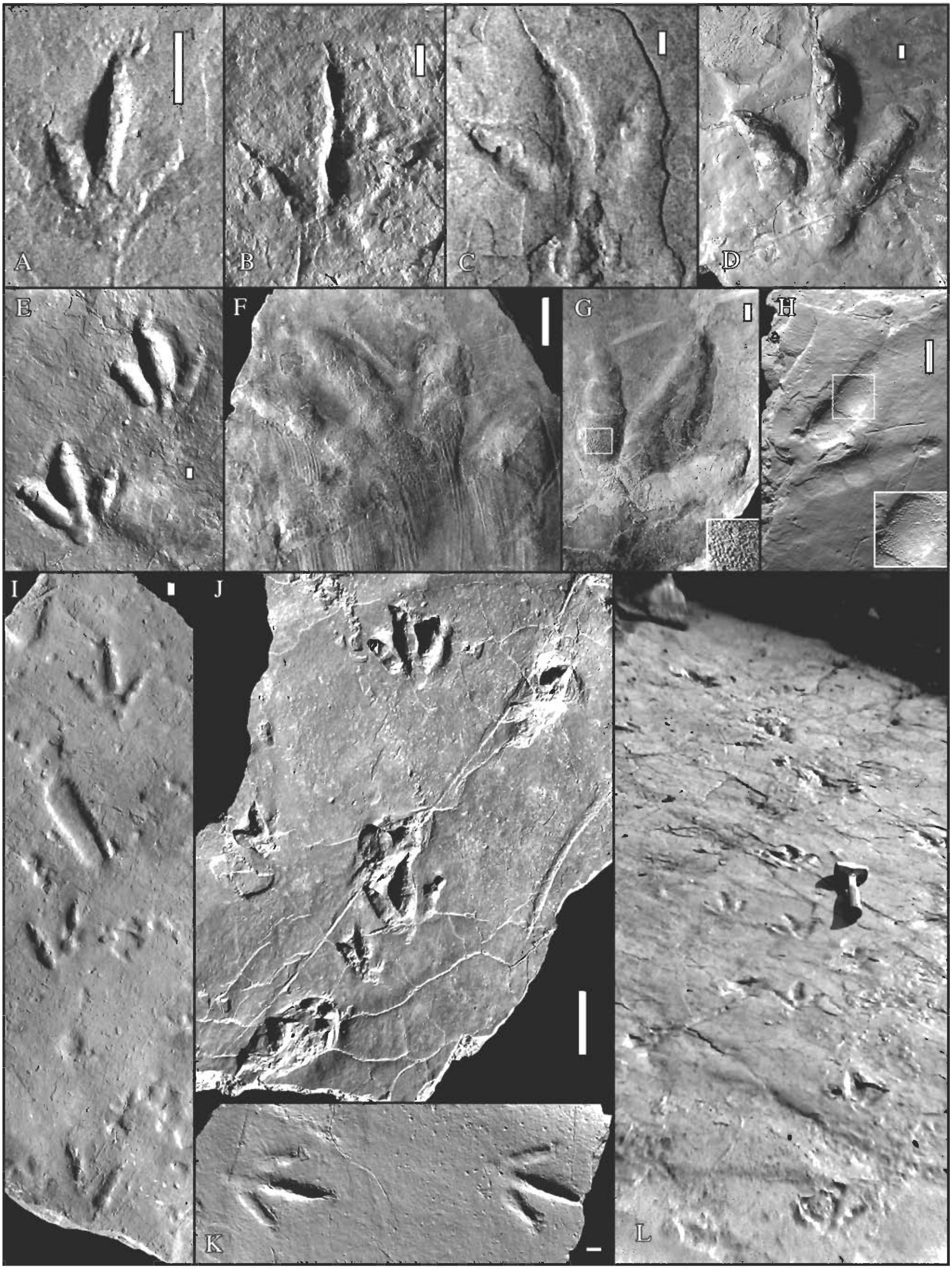
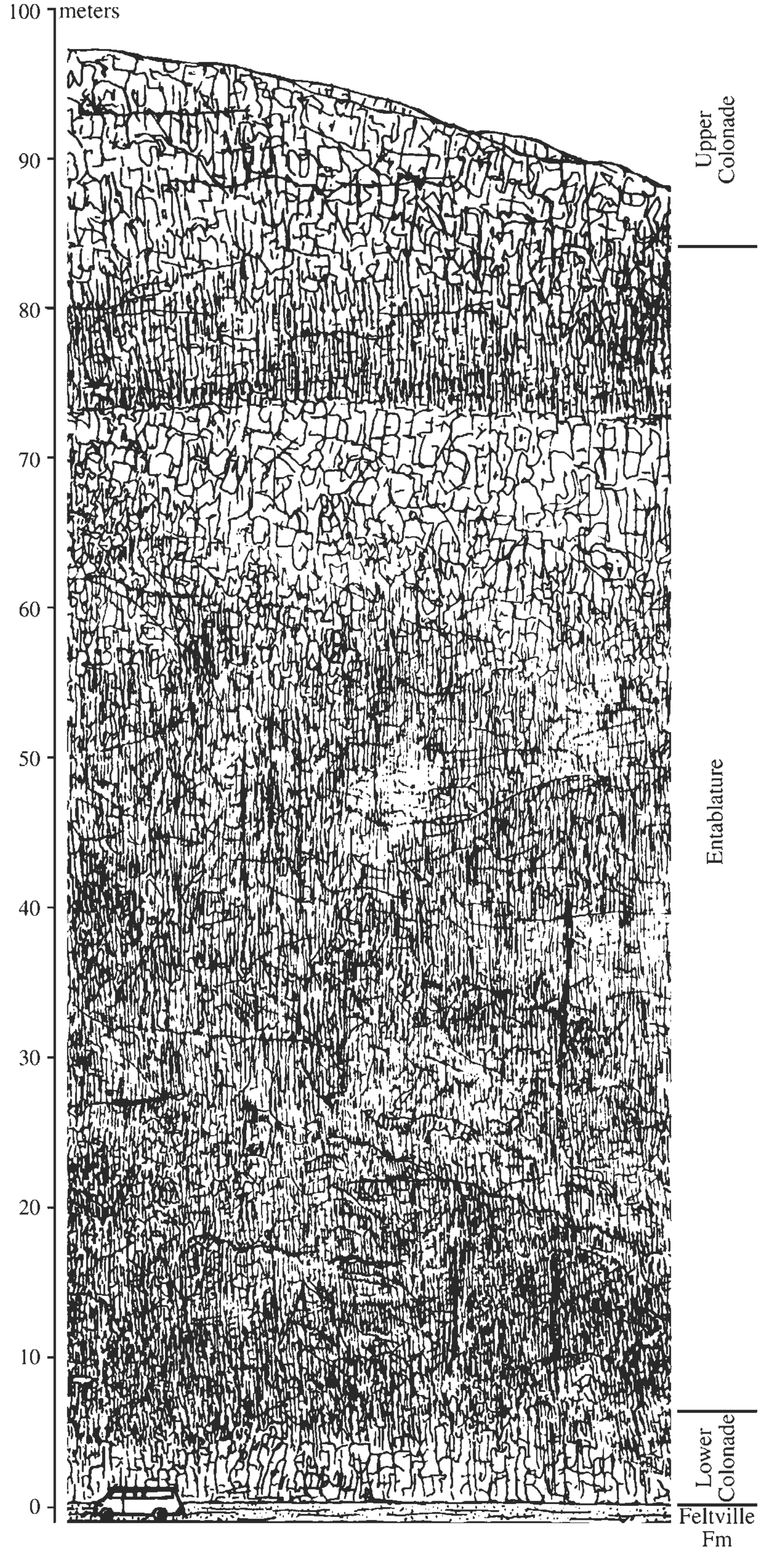
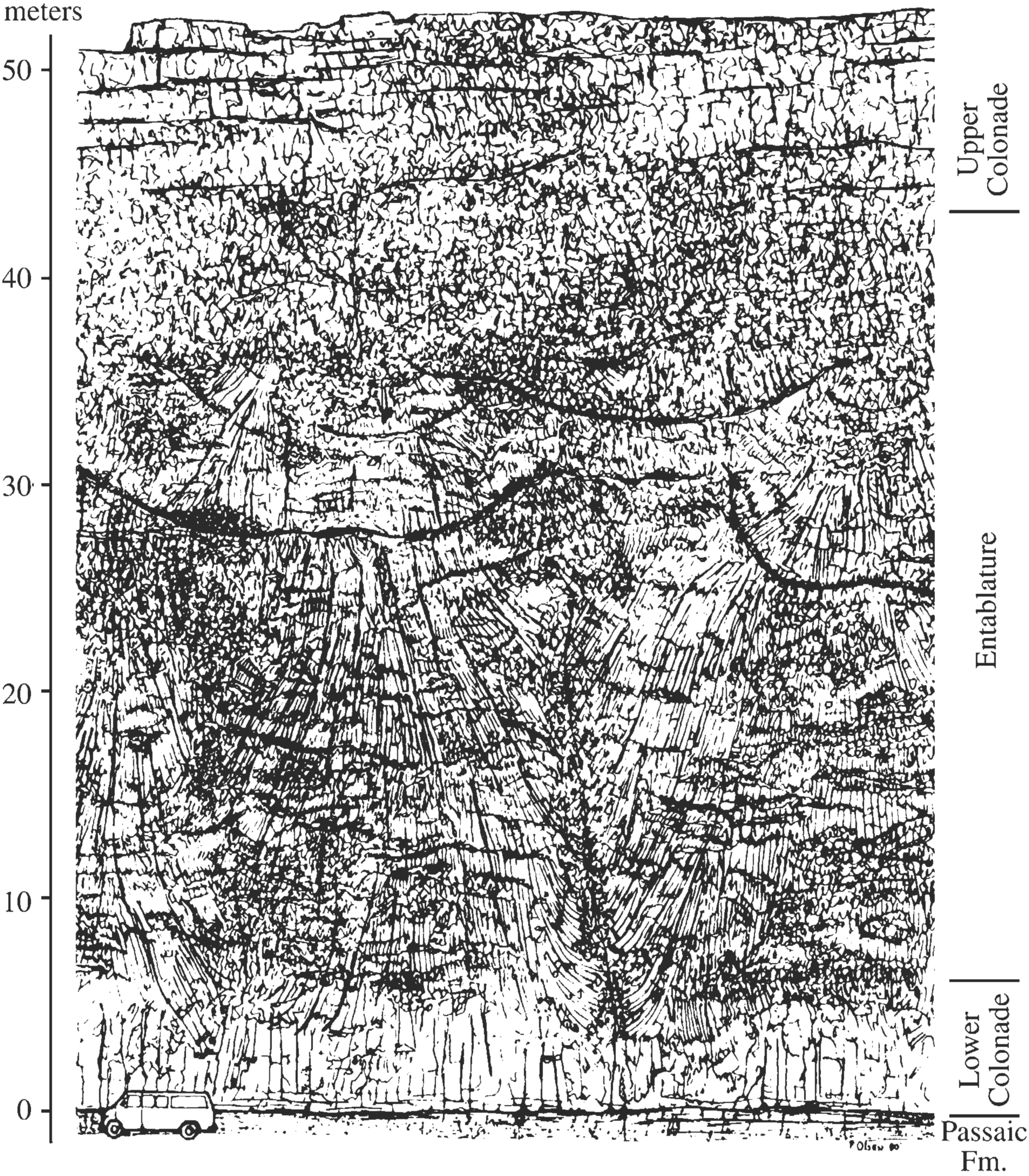


Figure 45



100
meters
90
80
70
60
50
40
30
20
10
0
Upper Colonade
Entablature
Lower Colonade
Feltville Fm

Figure 46



meters
50
40
30
20
10
0
Upper Colonade
Entablature
Lower Colonade
Passaic Fm.

Figure 47

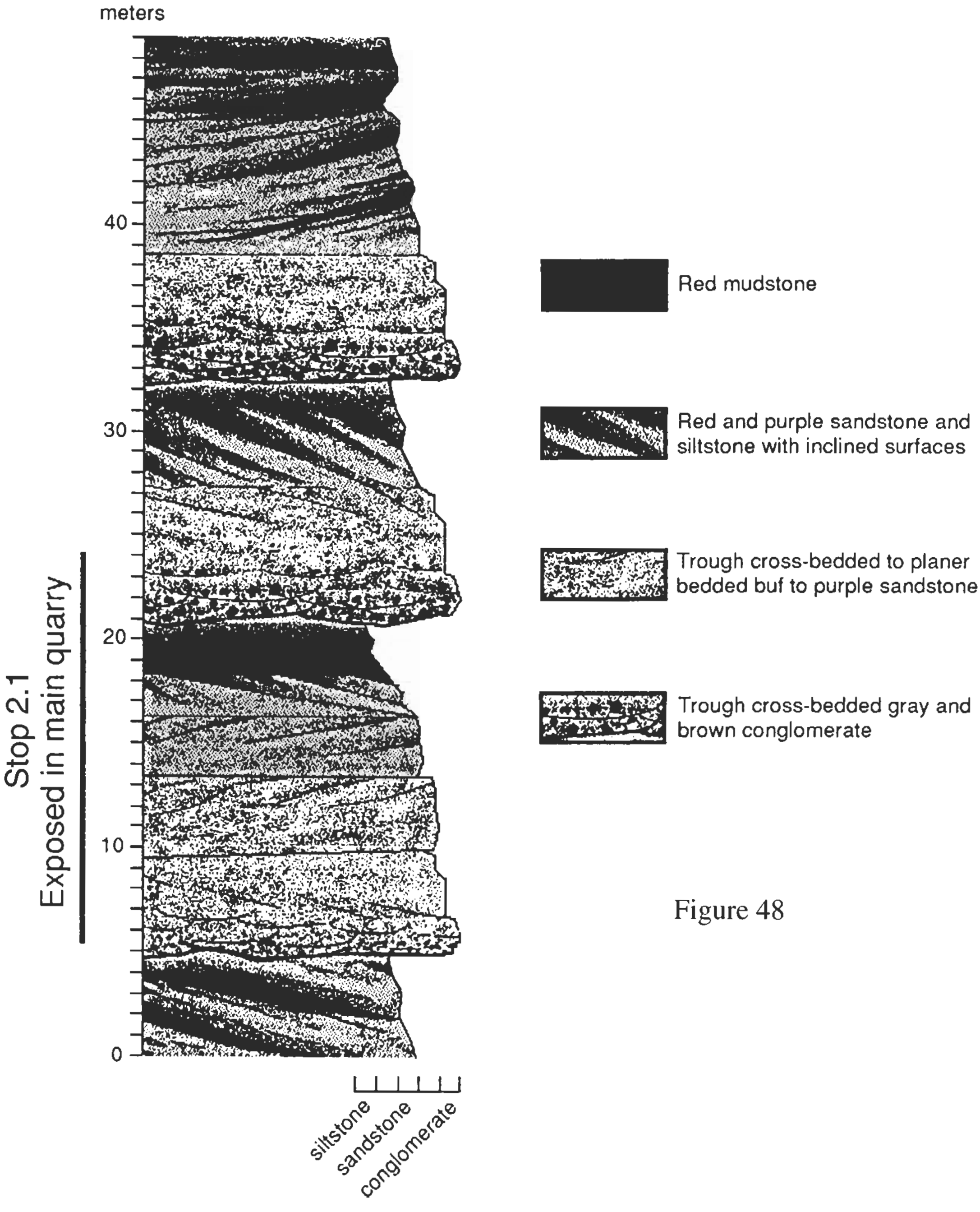

meters
40
30
20
10
0
Stop 2.1
Exposed in main quarry
siltstone
sandstone
conglomerate
Red mudstone
Red and purple sandstone and siltstone with inclined surfaces
Trough cross-bedded to planer bedded buf to purple sandstone
Trough cross-bedded gray and brown conglomerate

Figure 48

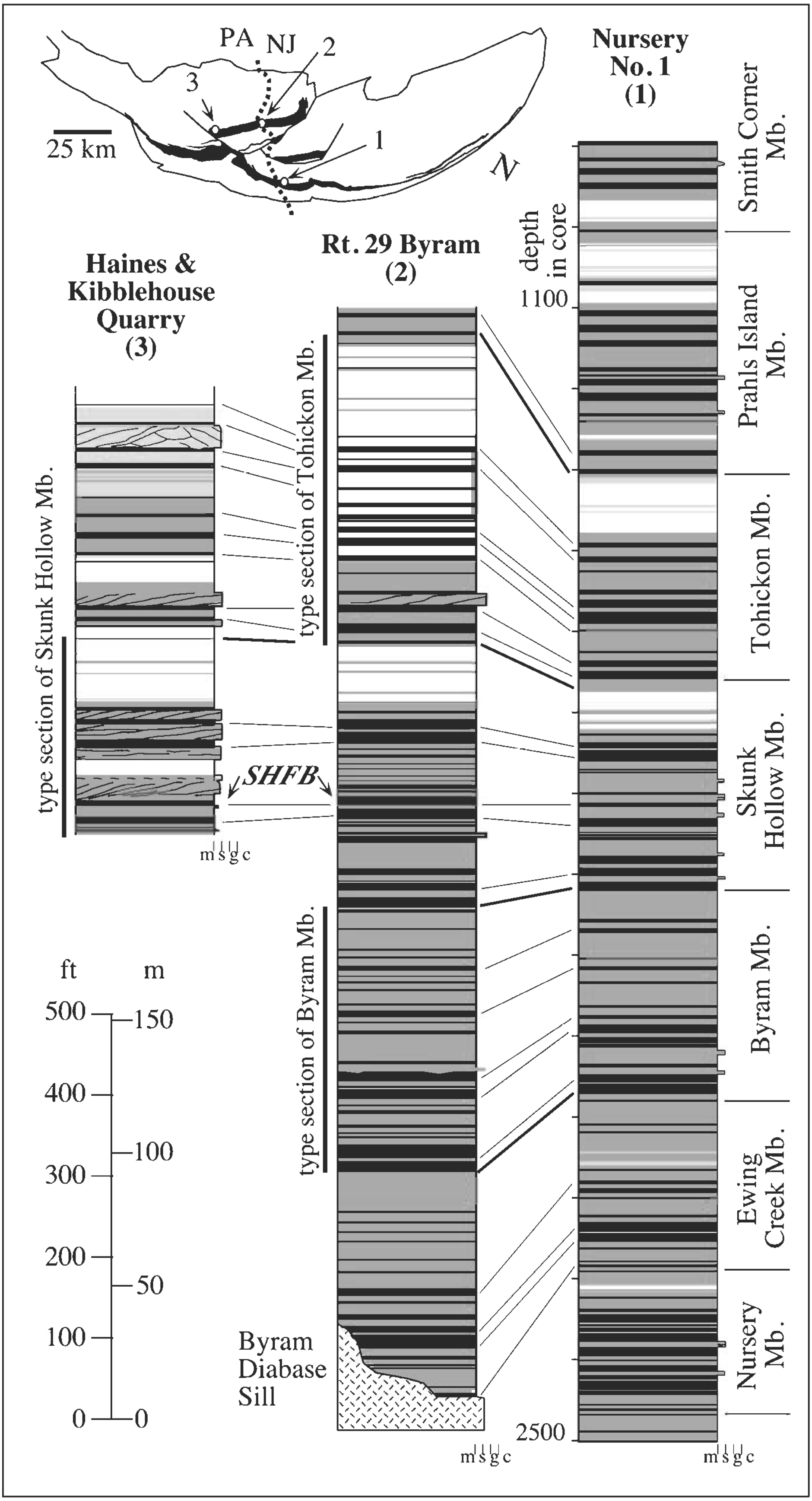
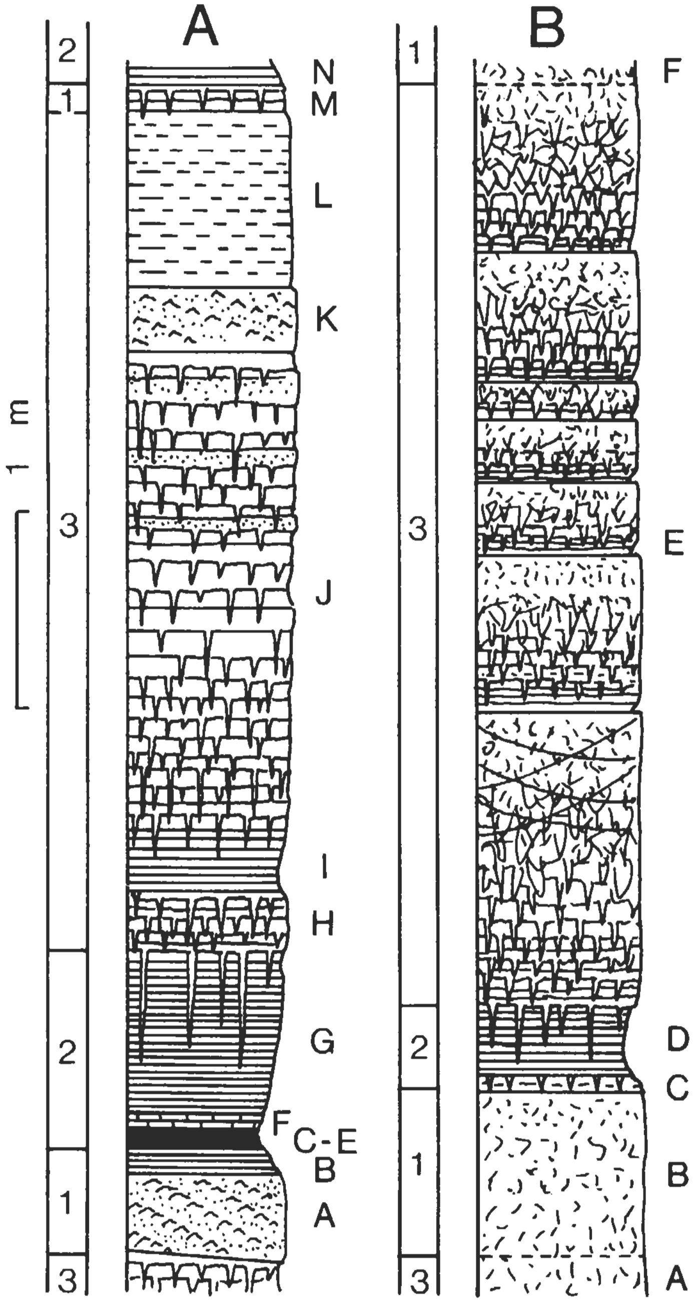

PA
NJ
1
2
3
25 km
N
Nursery No. 1 (1)
Rt. 29 Byram (2)
Haines & Kibblehouse Quarry (3)
depth in core
1100
2500
Smith Corner Mb.
Prahls Island Mb.
Tohickon Mb.
Skunk Hollow Mb.
Byram Mb.
Ewing Creek Mb.
Nursery Mb.
type section of Tohickon Mb.
type section of Skunk Hollow Mb.
type section of Byram Mb.
SHFB
Byram Diabase Sill
ft
m
500
400
300
200
100
0
150
100
50
0
m s g c

Figure 49

Figure 50



A

- N +30 cm black laminated claystone (2.9% TOC).
- M 10 cm gray mudstone with widely-spaced desiccation cracks.
- L 96 cm massive, seemingly structureless, monosulfide-bearing gray mudstone (0.6% TOC).
- K 30 cm gray fine-grained, oscillatory-rippled sandstone.
- J 240 cm gray decimeter-scale siltstone and fine sandstone beds with abundant contorted desiccation cracks, soft sediment deformation, reptile footprints (*Apatopus*), and rare clam shrimp (*Cyzicus*)(0.5% TOC).
- I 30 cm dark gray, laminated mudstone with rare fish bones (0.1% TOC).
- H 30 cm dark gray, centimeter-scale mudstone beds with widely-spaced, deep, contorted desiccation cracks (1.3 % TOC).
- G 83 cm black, laminated, organic-rich (5.0% TOC) limestone (77% carbonate) grading up into less calcareous (34% carbonate) and less organic rich (1.6% TOC) siltstone with deep, widely-spaced, and sinuous desiccation cracks originating in the overlying beds. Abundant pinch and swell laminae present. Clam shrimp (*Cyzicus*) and ostracodes (*Darwinula*) abundant at the base but absent at top.
- F 3 cm black, laminated, organic-rich (6.6% TOC) blebby limestone (76% carbonate) with occasional microlaminae. Abundant ostracodes (*Darwinula*) and clam shrimp (*Cyzicus*) present.
- E 8 cm black, microlaminated limestone with even microlamination and some pronounced stylolites passing up into limestones with very discontinuous blebby microlaminae. Clam shrimp (*Cyzicus*), ostracodes (*Darwinula*), fish (*Turseodus* and *Synorichthyes*) , and coprolites present.
- D 3 cm black, microlaminated blebby calcareous siltstone with extremely abundant clam shrimp (*Cyzicus*), articulated fish (*Turseodus*), and coprolites.
- C 4 cm black, microlaminated calcareous claystone (1.4% TOC, 33% carbonate). Basal few couplets with articulated reptiles (*Tanytrachelos*) and rare clam shrimp (*Cyzicus*).
- B 12 cm black well-bedded mudstone showing an upward increase in thin-bedding and total organic content. Rare fish bones (?*Diplurus*) and clam shrimp (*Palaeolimnadia* and *Cyzicus*).
- A 39 cm gray, climbing ripple-bedded fine sandstone (0.3% TOC), Desiccation cracks are absent in contrast to underlying division 3 of the preceding cycle.

A

- F +20 cm gray massive mudstone with crumb fabric.
- E 491 cm consisting of 7 massive mudstone sequences, each 150 to 20 cm thick, showing upwards transition from thin-bedded claystone to breccia fabric to crumb fabric.
- D 31 cm red and green laminated to thin-bedded claystone with widely-spaced desiccation cracks projecting down from overlying unit.
- C 8 cm gray claystone becoming laminated upwards with widely-spaced desiccation cracks at top.
- B 82 cm gray massive mudstone with well-developed crumb fabric with analcime filled vesicles.

Figure 51. Warford Mb. and member C.

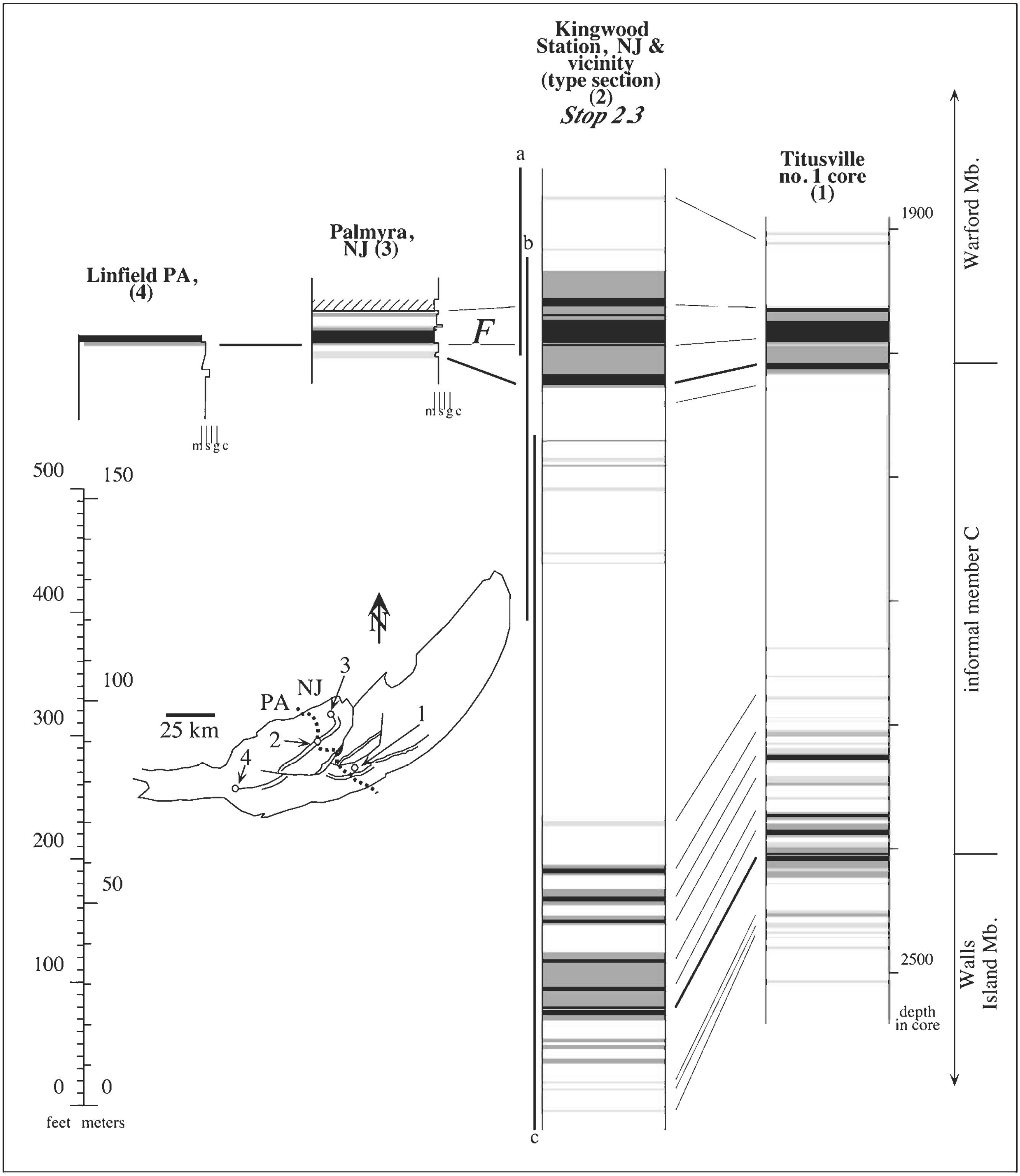
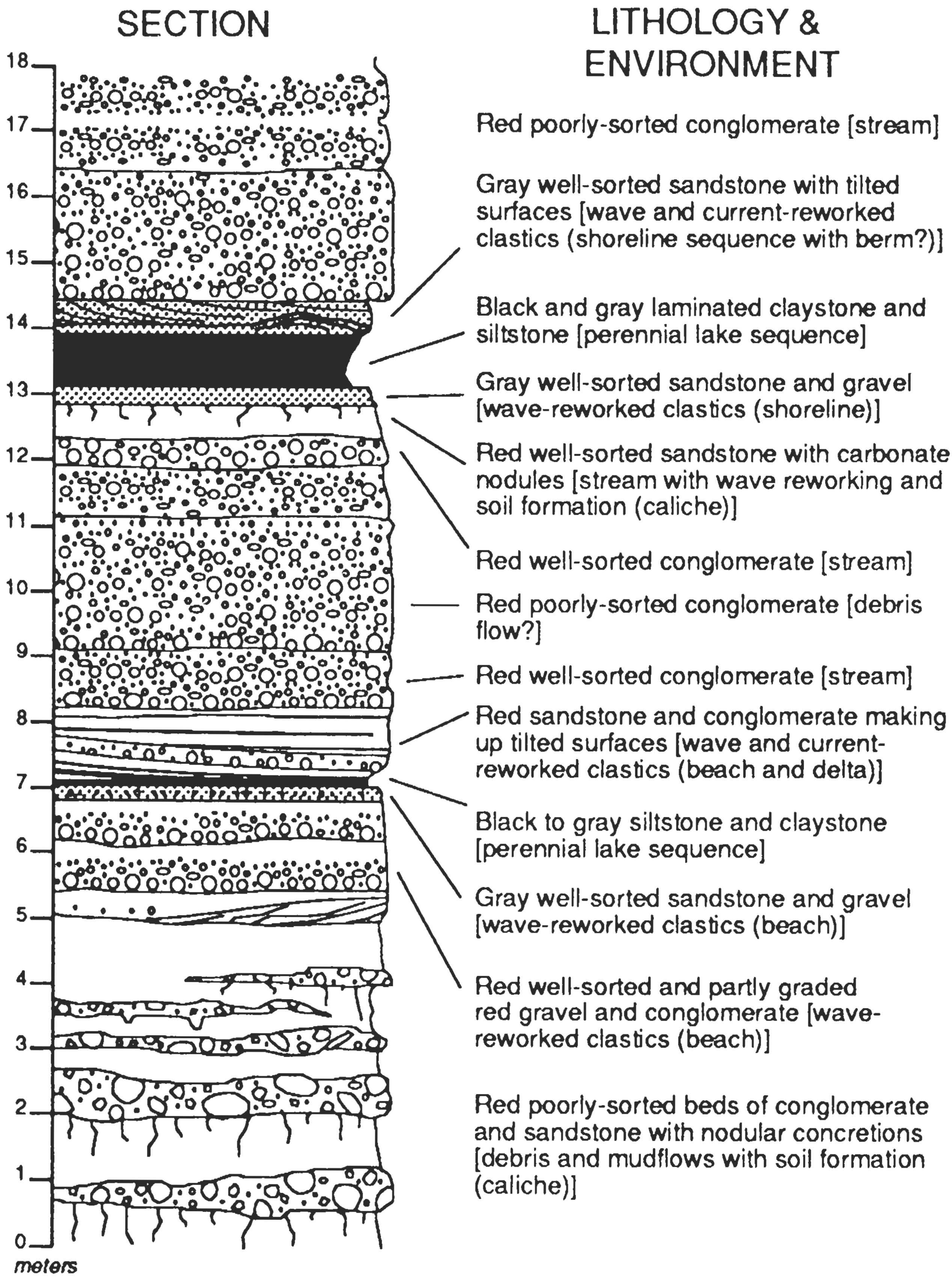
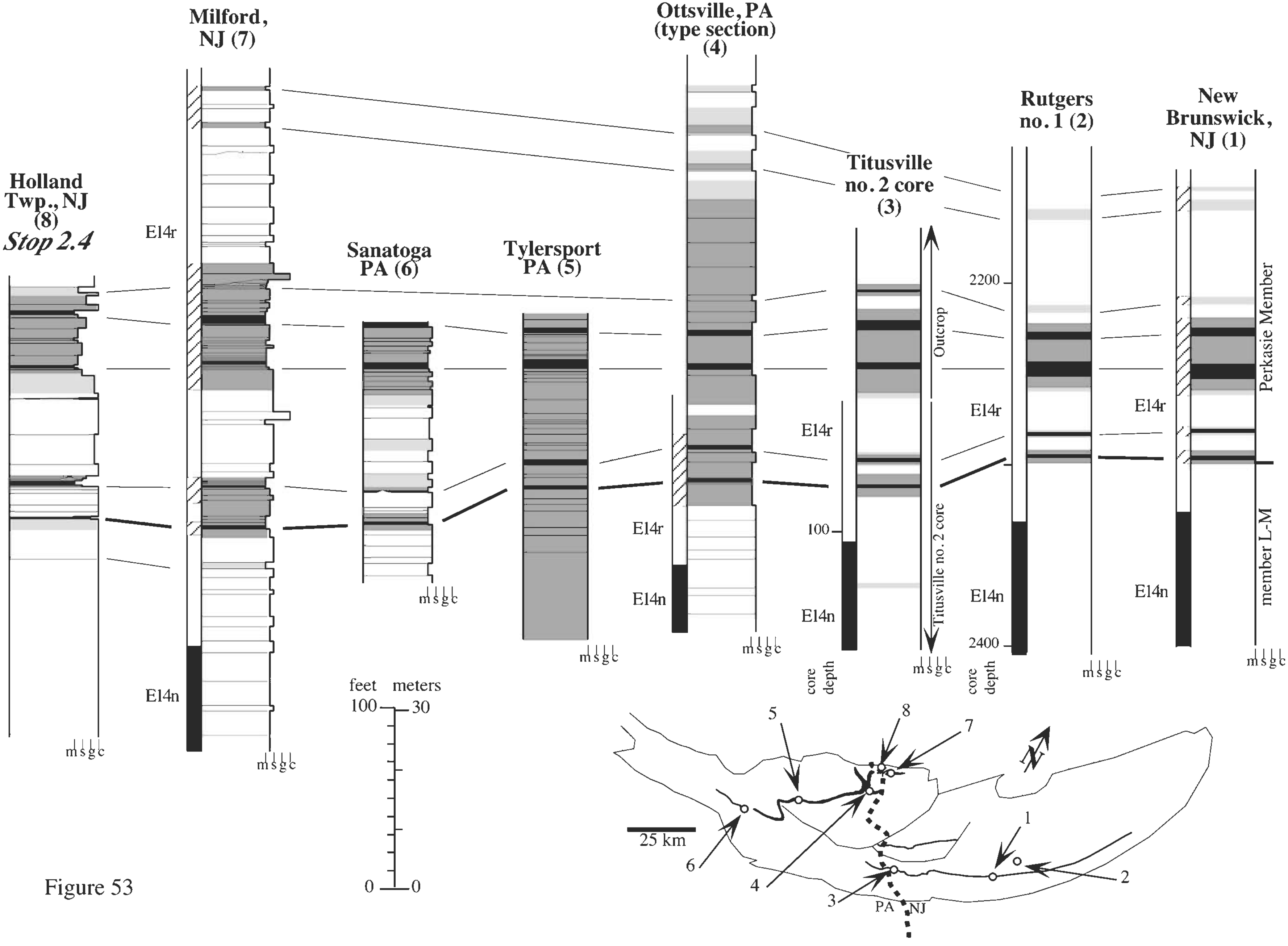


Figure 52


SECTION
LITHOLOGY & ENVIRONMENT
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
meters
Red poorly-sorted conglomerate [stream]
Gray well-sorted sandstone with tilted surfaces [wave and current-reworked clastics (shoreline sequence with berm?)]
Black and gray laminated claystone and siltstone [perennial lake sequence]
Gray well-sorted sandstone and gravel [wave-reworked clastics (shoreline)]
Red well-sorted sandstone with carbonate nodules [stream with wave reworking and soil formation (caliche)]
Red well-sorted conglomerate [stream]
Red poorly-sorted conglomerate [debris flow?]
Red well-sorted conglomerate [stream]
Red sandstone and conglomerate making up tilted surfaces [wave and current-reworked clastics (beach and delta)]
Black to gray siltstone and claystone [perennial lake sequence]
Gray well-sorted sandstone and gravel [wave-reworked clastics (beach)]
Red well-sorted and partly graded red gravel and conglomerate [wave-reworked clastics (beach)]
Red poorly-sorted beds of conglomerate and sandstone with nodular concretions [debris and mudflows with soil formation (caliche)]



Holland Twp., NJ (8)
Stop 2.4
Milford, NJ (7)
Sanatoga PA (6)
Tylersport PA (5)
Ottsville, PA (type section) (4)
Titusville no. 2 core (3)
Rutgers no. 1 (2)
New Brunswick, NJ (1)
E14r
E14n
Outcrop
Titusville no. 2 core
core depth
100
2200
2400
Perkasie Member
member L-M
m s g c
feet meters
100 30
0 0
25 km
PA NJ
1
2
3
4
5
6
7
8

Figure 53

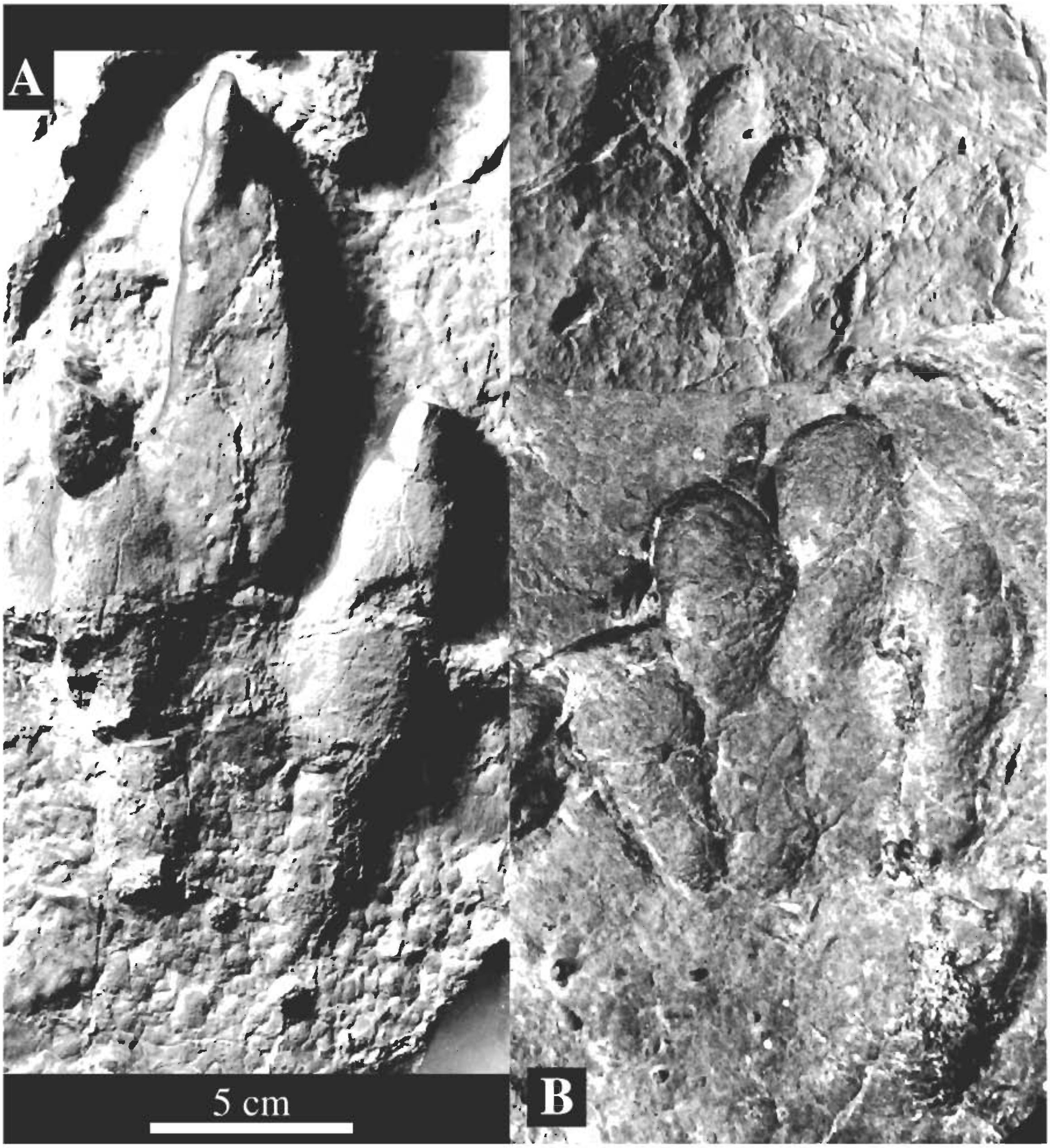


Figure 54

Figure 55

Metlars Member, Pottstown, PA

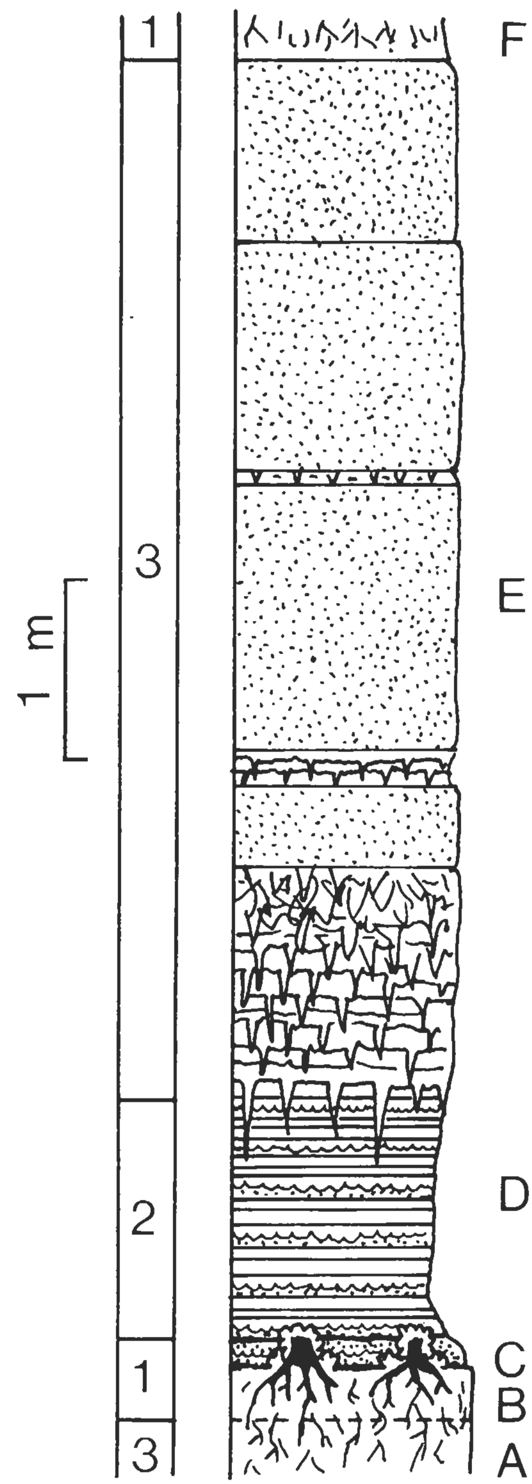
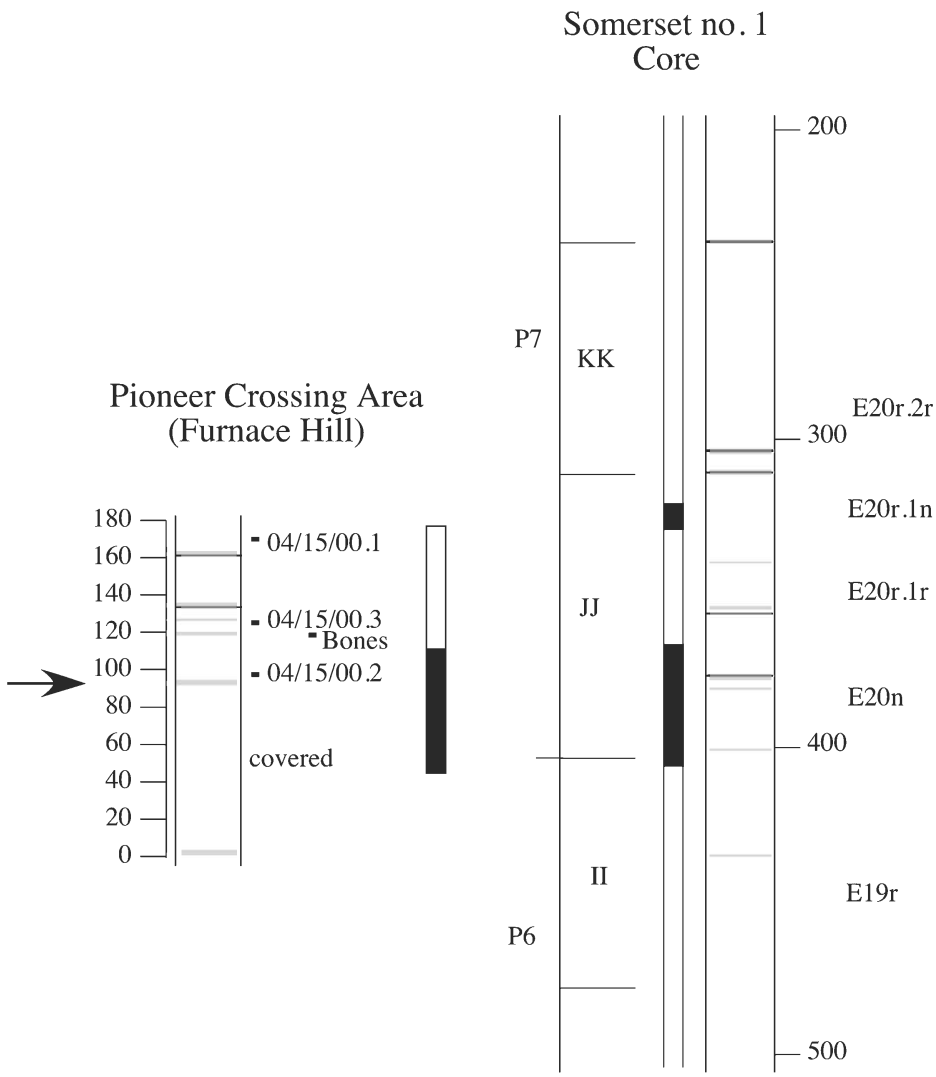


Figure 56. Member JJ.



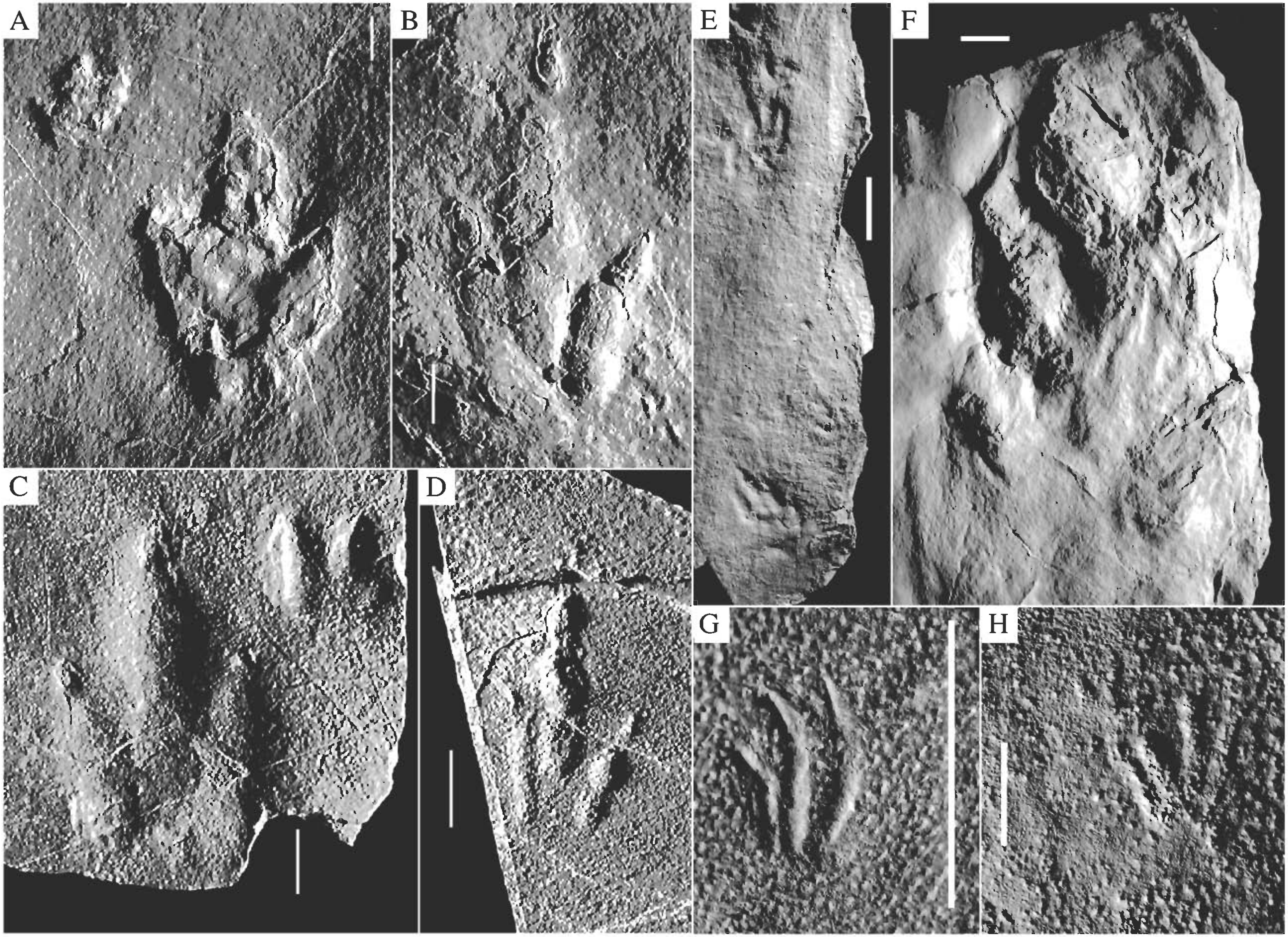


Figure 57

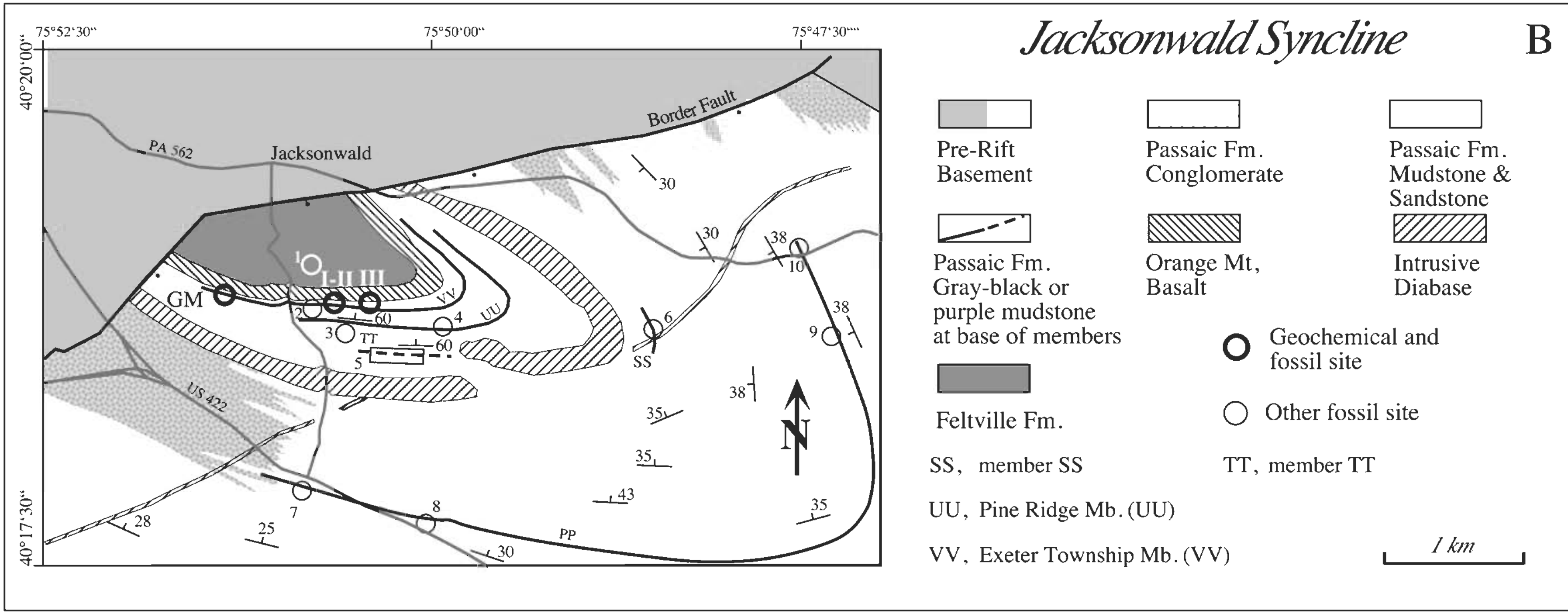
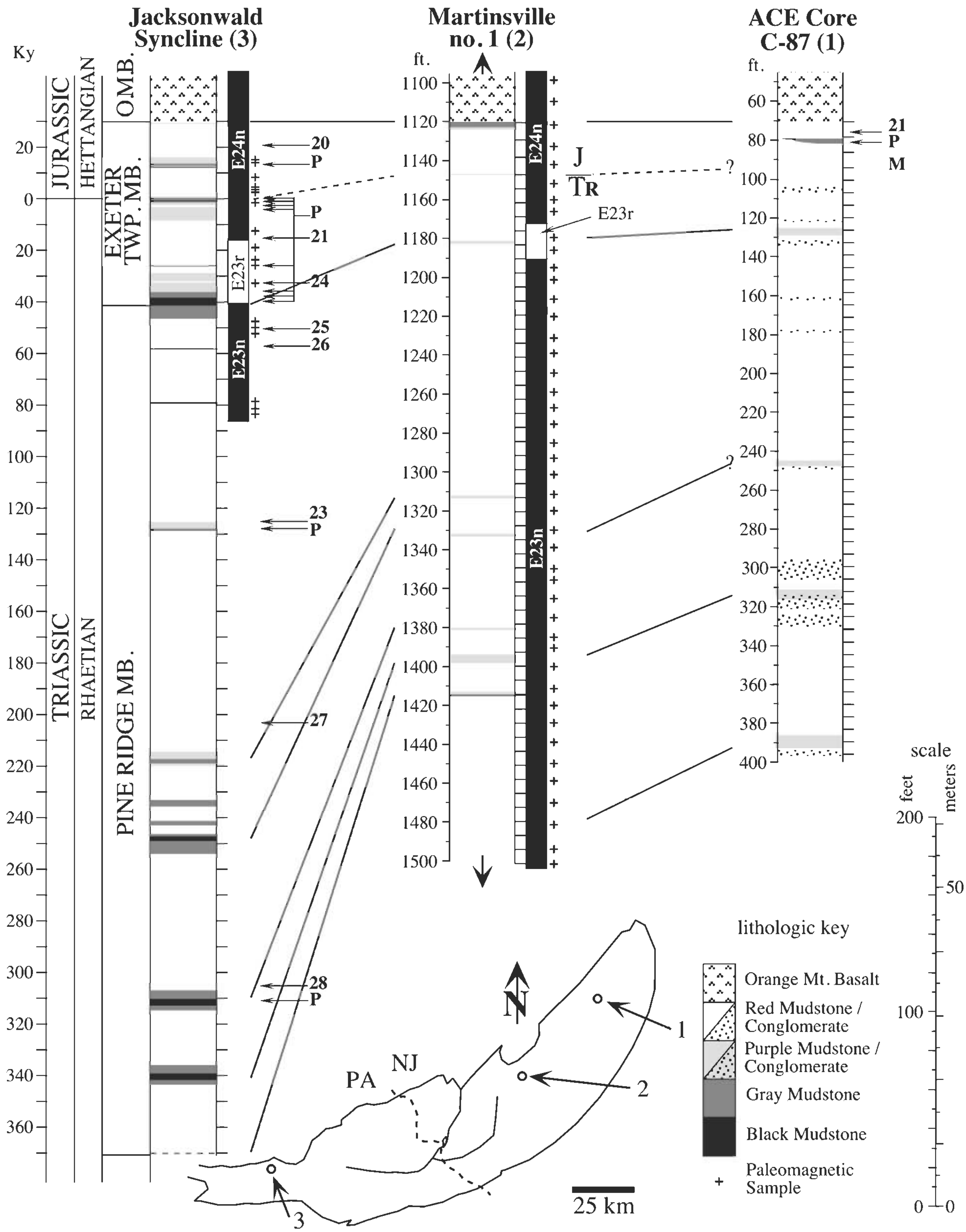

Jacksonwald Syncline
B
75°52'30"
75°50'00"
75°47'30"
40°20'00"
40°17'30"
Border Fault
PA 562
Jacksonwald
US 422
GM
I-II III
SS
TT
UU
VV
PP
Pre-Rift Basement
Passaic Fm. Conglomerate
Passaic Fm. Mudstone & Sandstone
Passaic Fm. Gray-black or purple mudstone at base of members
Orange Mt, Basalt
Intrusive Diabase
Feltville Fm.
Geochemical and fossil site
Other fossil site
SS, member SS
TT, member TT
UU, Pine Ridge Mb. (UU)
VV, Exeter Township Mb. (VV)
1 km

Figure 58

Figure 59



Jacksonwald Syncline (3)
Martinsville no. 1 (2)
ACE Core C-87 (1)
Ky
ft.
JURASSIC
HETTANGIAN
TRIASSIC
RHAETIAN
OMB.
EXETER TWP. MB.
PINE RIDGE MB.
E24n
E23r
E23n
J
TR
E23r
20
P
21
24
25
26
23
27
28
M
scale
feet
meters
lithologic key
Orange Mt. Basalt
Red Mudstone / Conglomerate
Purple Mudstone / Conglomerate
Gray Mudstone
Black Mudstone
Paleomagnetic Sample
N
PA
NJ
25 km

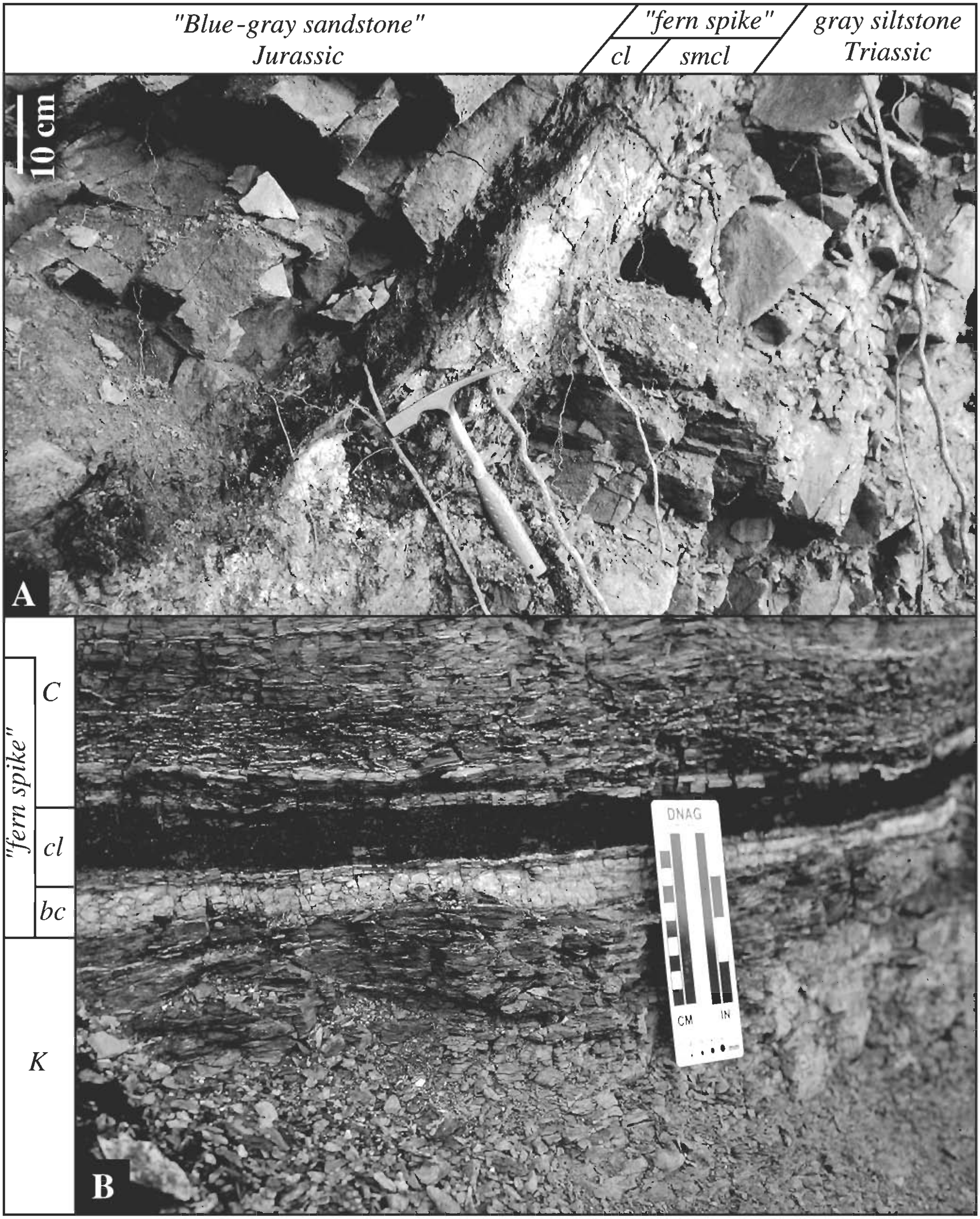


Figure 60 Triassic-Jurassic (above) and K-T (below) boundaries

Jacksonwald Syncline Triassic-Jurassic Boundary

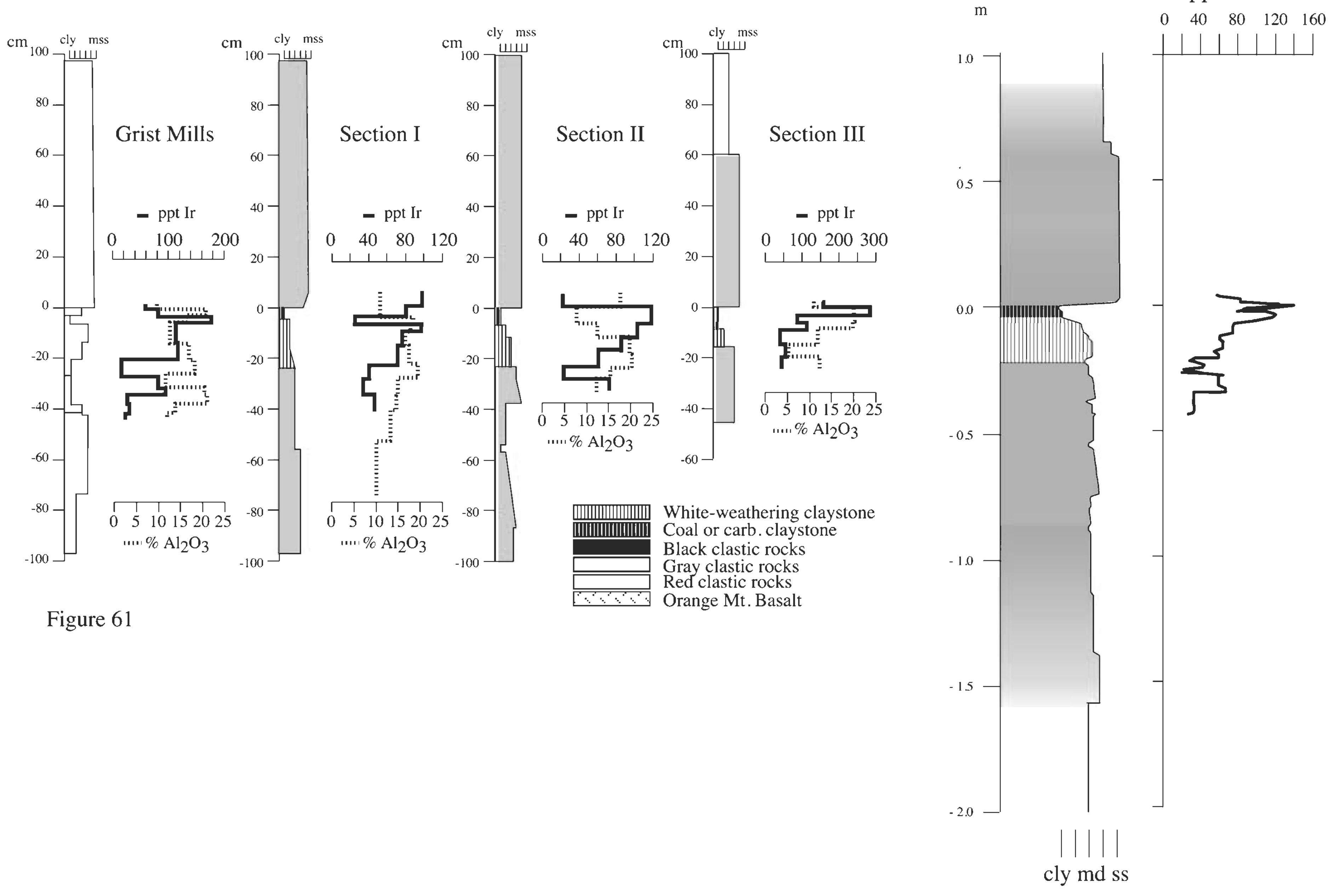


Figure 61

Figure 62 Track slab from the very latest Triassic.

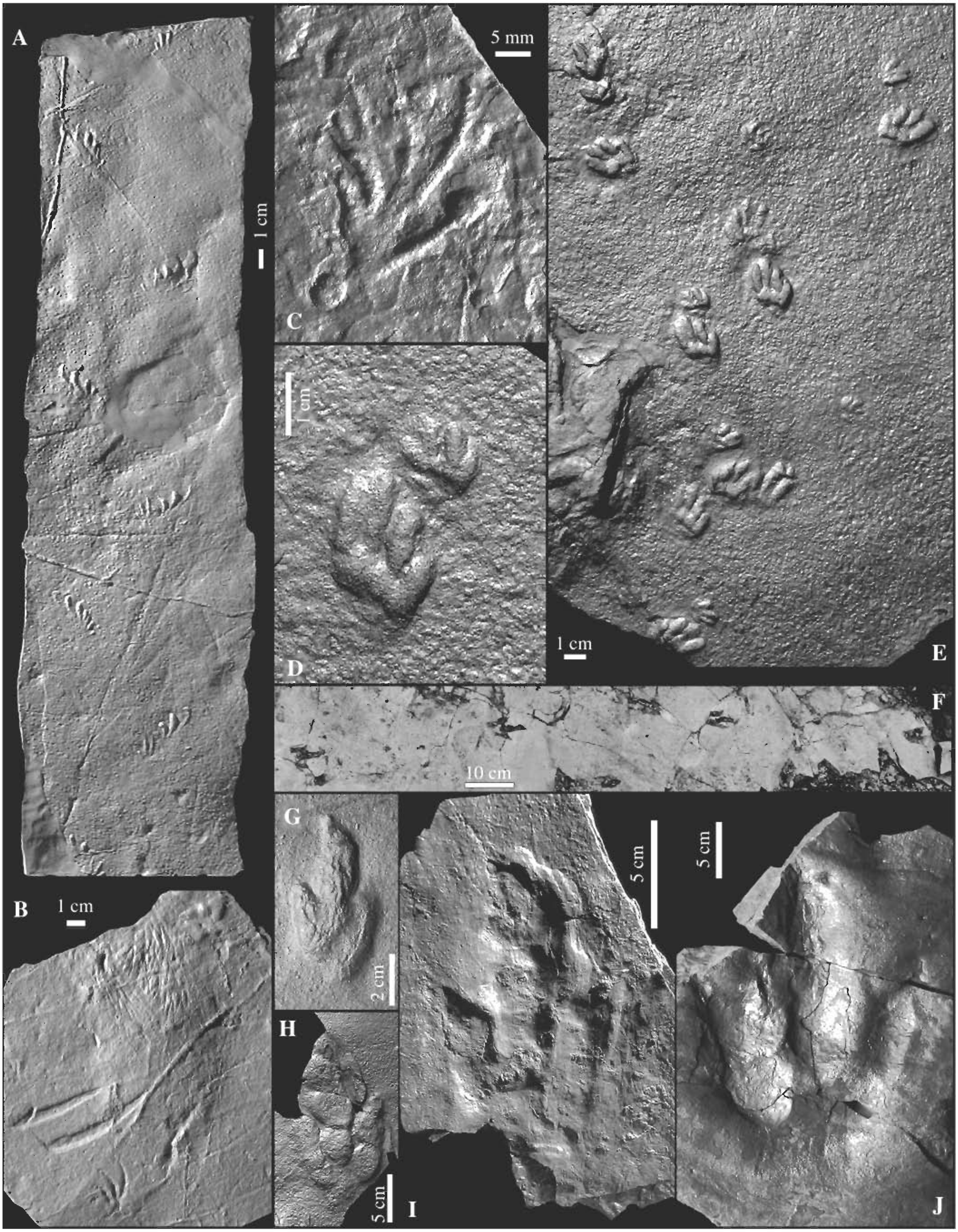


Figure 63 Footpints of the earliest Jurassic of the uppermost Passaic Fm.

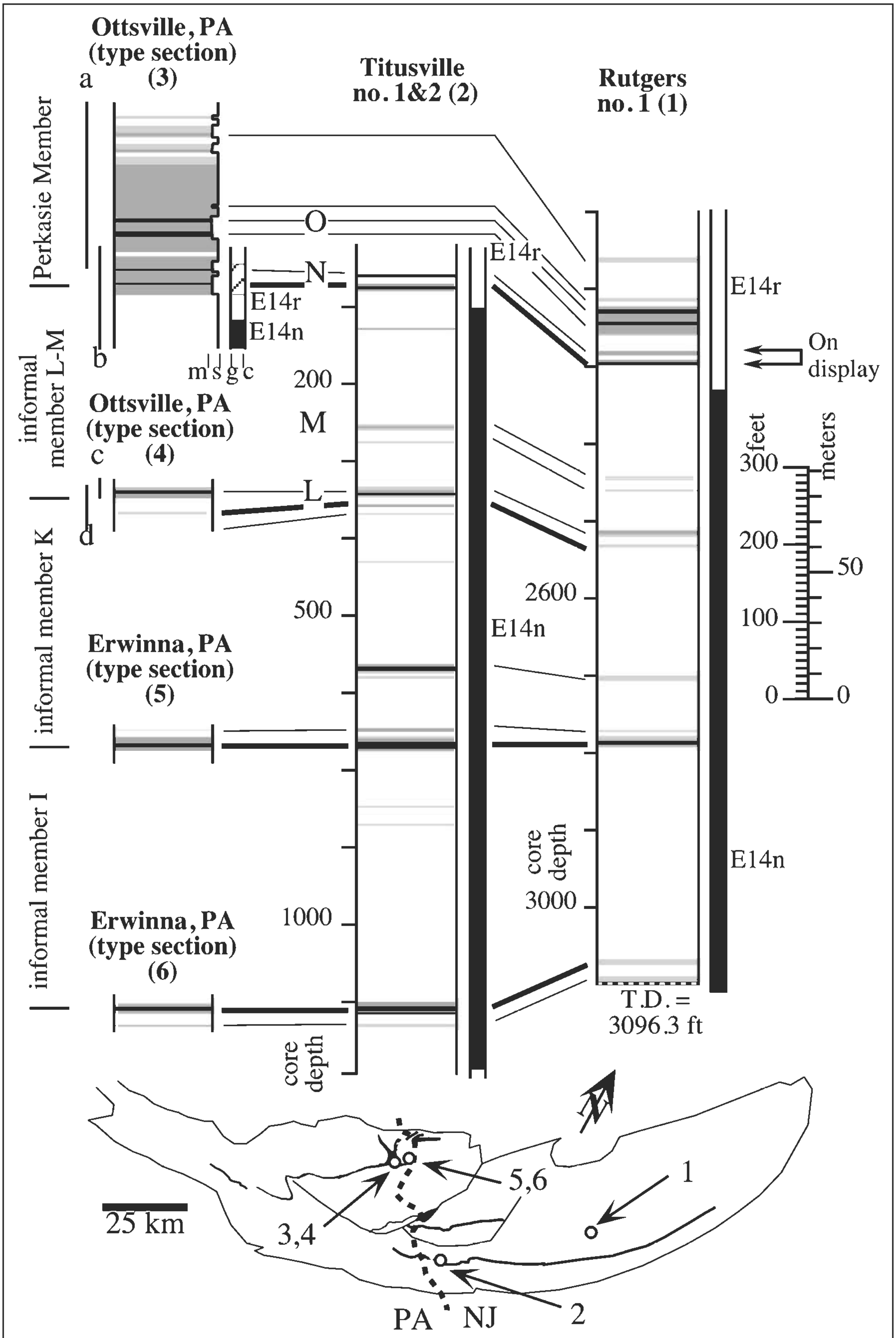


Figure 64 Lower Perkasie Member

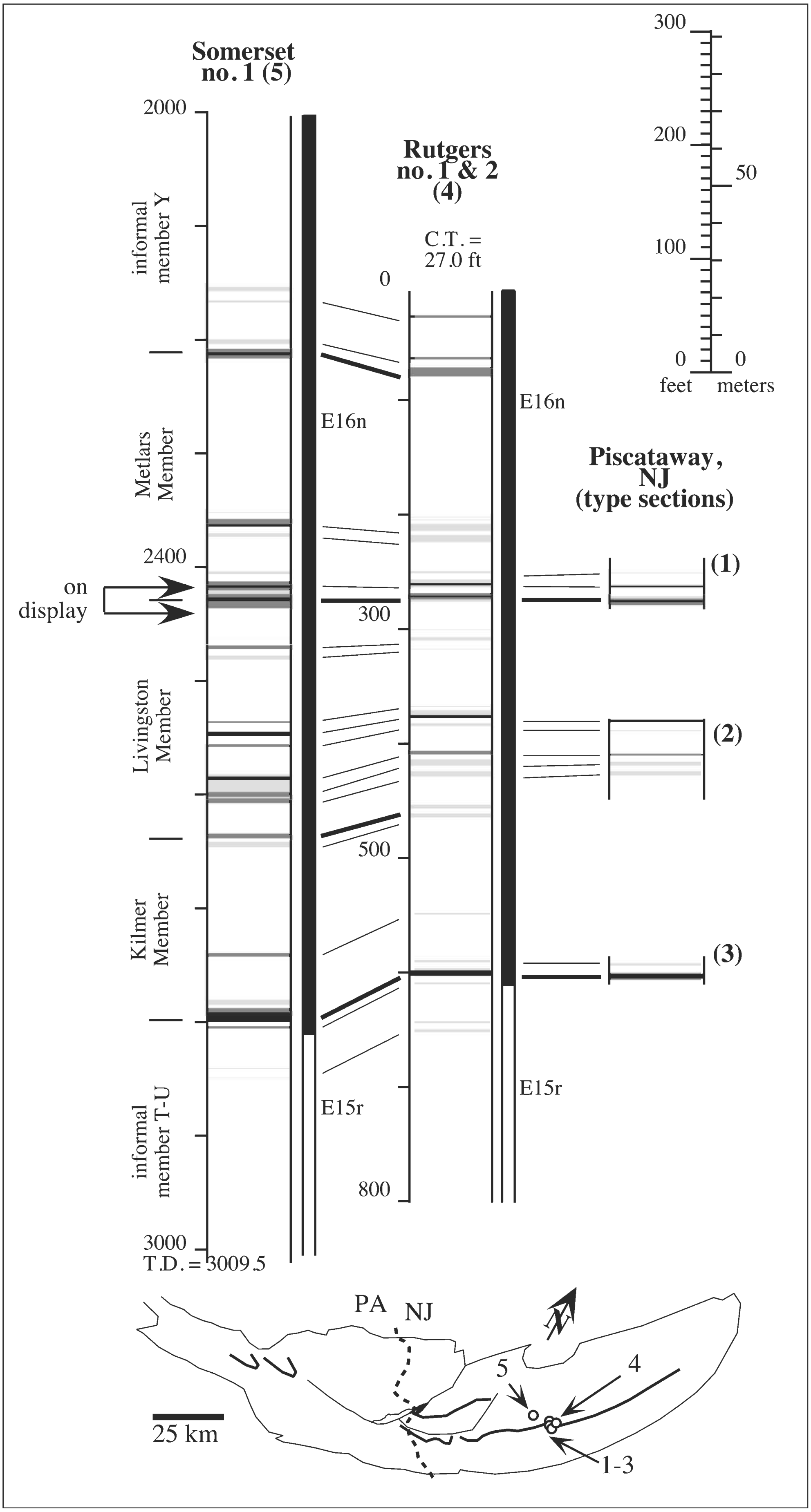


Figure 65. Lower Metlars Member in the overlap between Rutgers and Somerset cores.

Feltville ACE Cores

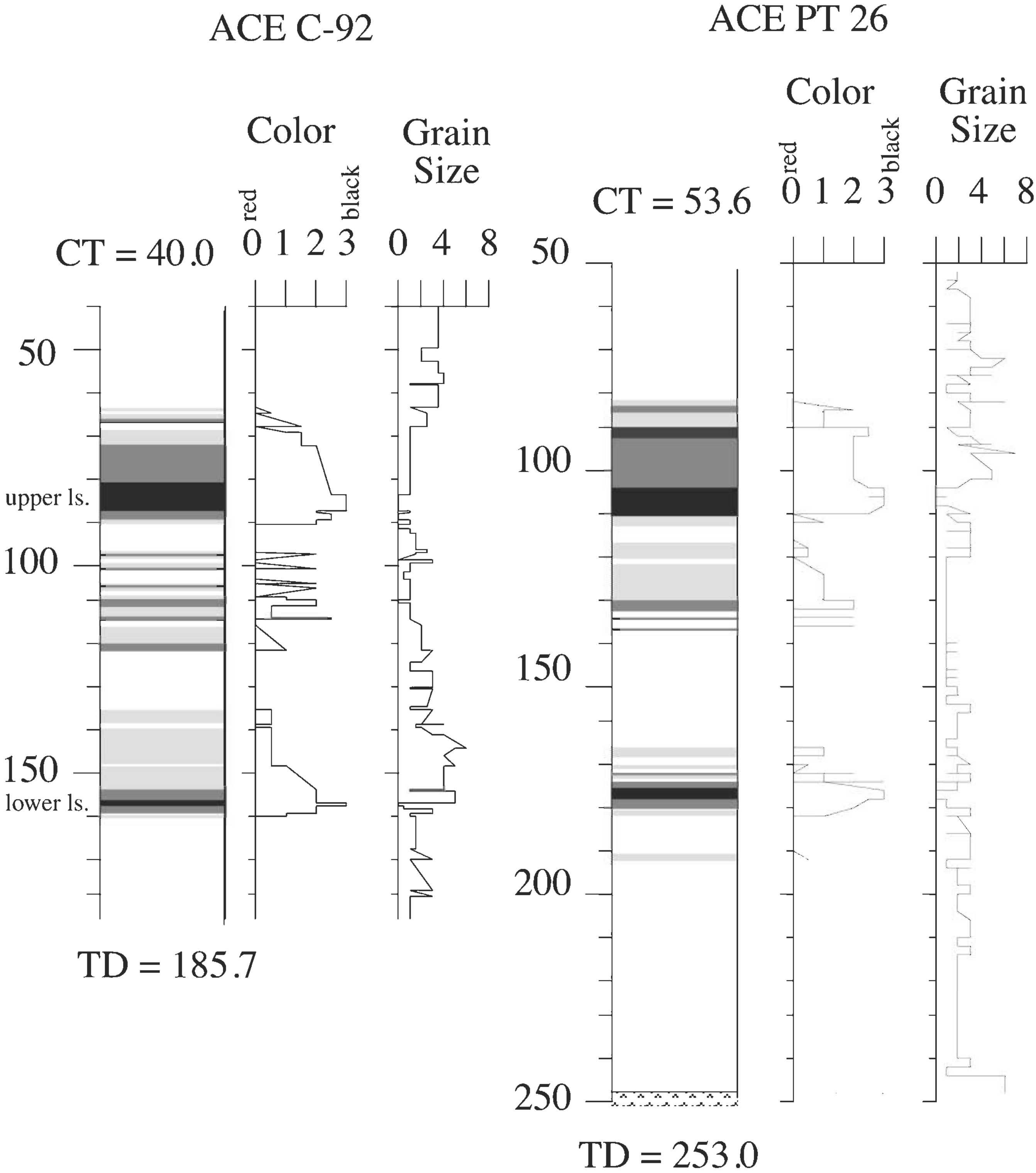


Figure 66

Cores B-1 and PT - 26

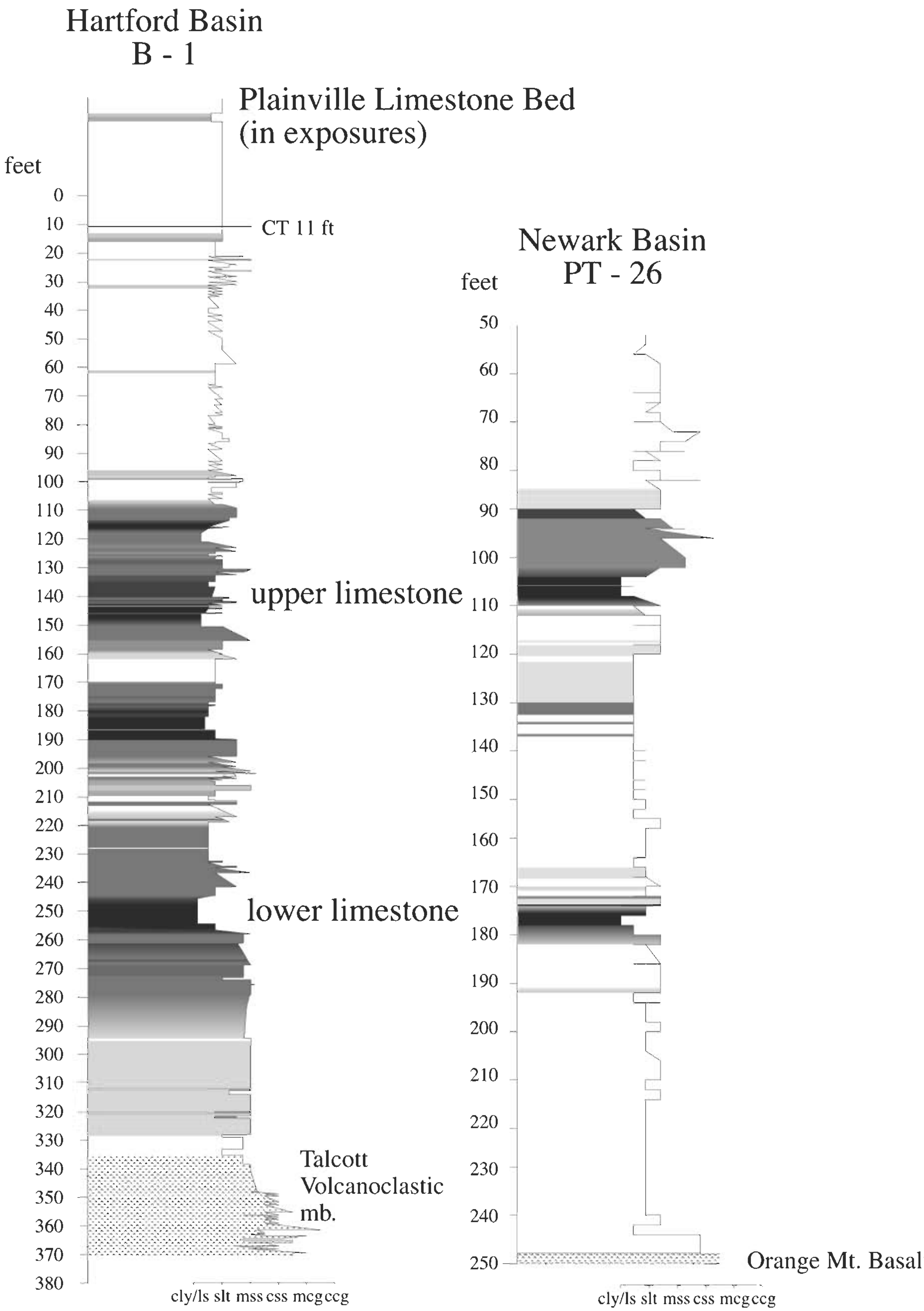


Figure 67

Exposures at Stop 4.1, Chersire, CT

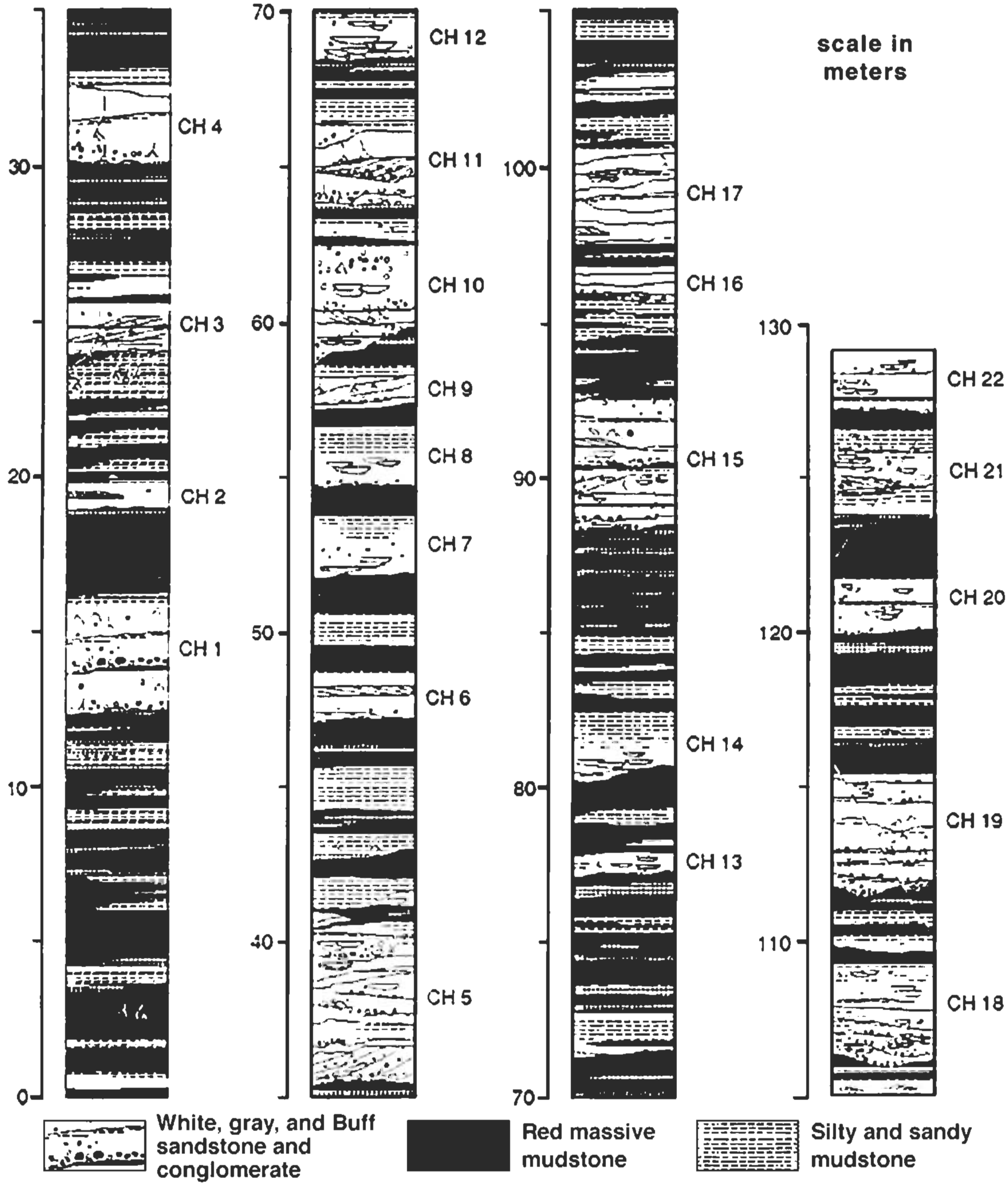
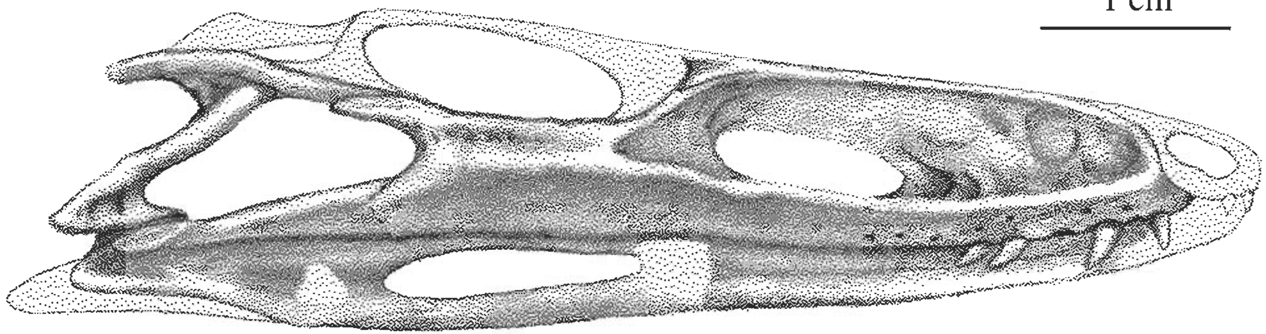


Figure 68

Erpetosuchus sp., New Haven Fm., Cheshire, CT.



Reconstruction

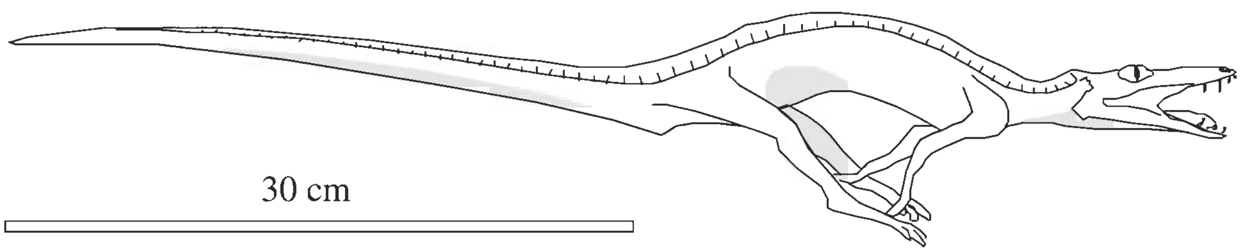


Figure 69

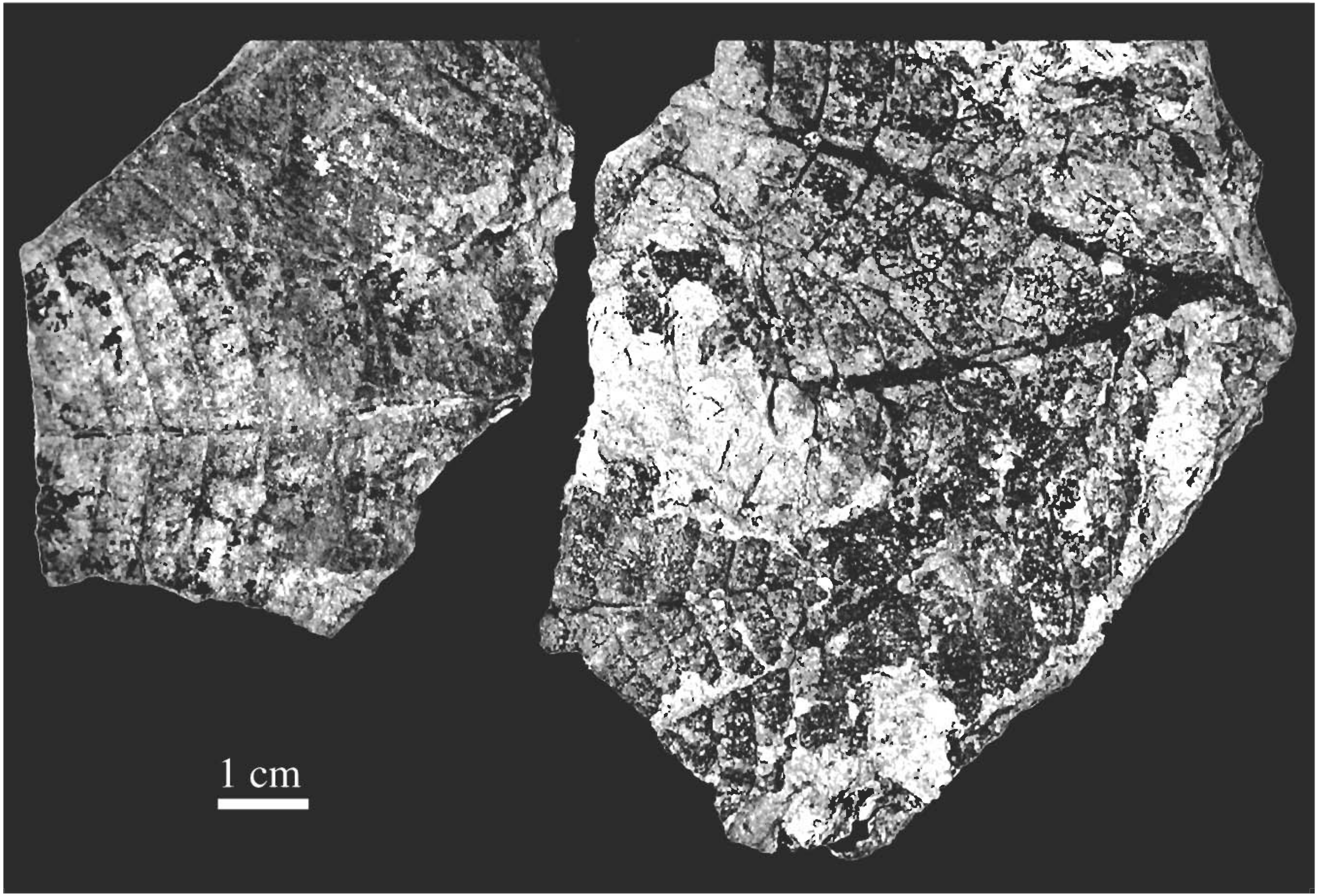
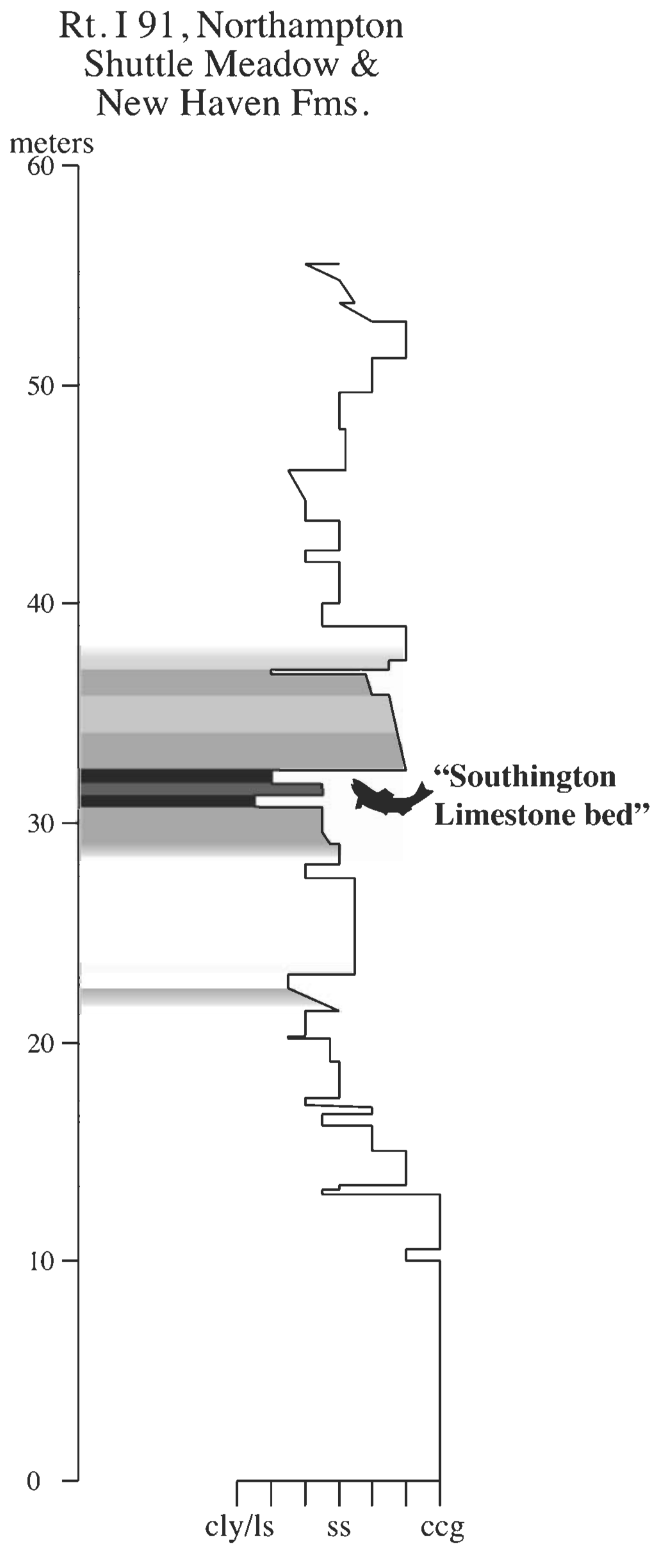


Figure 70. *Clathropteris meniscoides* from Stop 4.2.

Figure 71


Rt. I 91, Northampton
Shuttle Meadow &
New Haven Fms.
meters
60
50
40
30
20
10
0
"Southington
Limestone bed"
cly/ls
ss
ccg

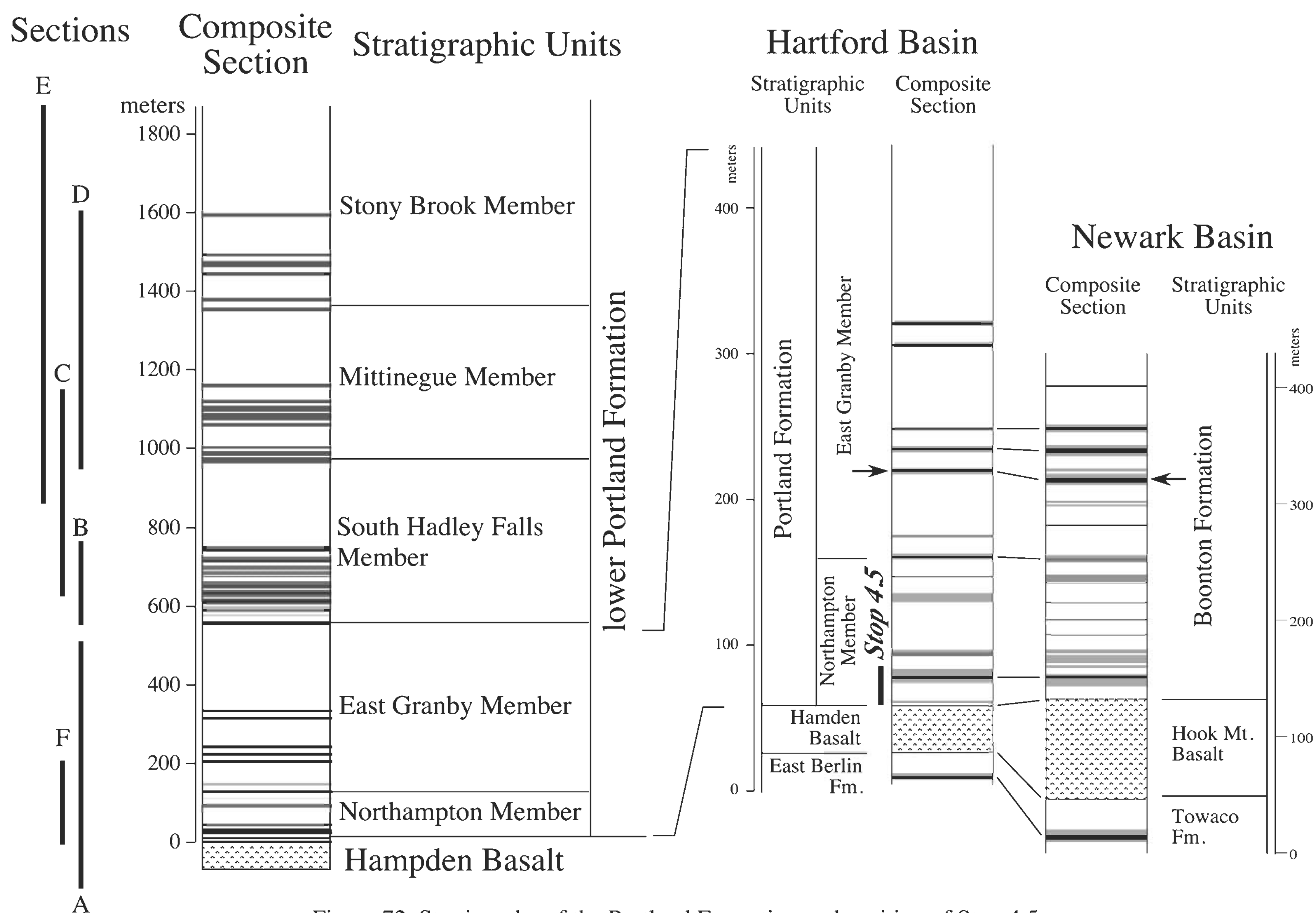


Figure 72. Stratigraphy of the Portland Formation and position of Stop 4.5.

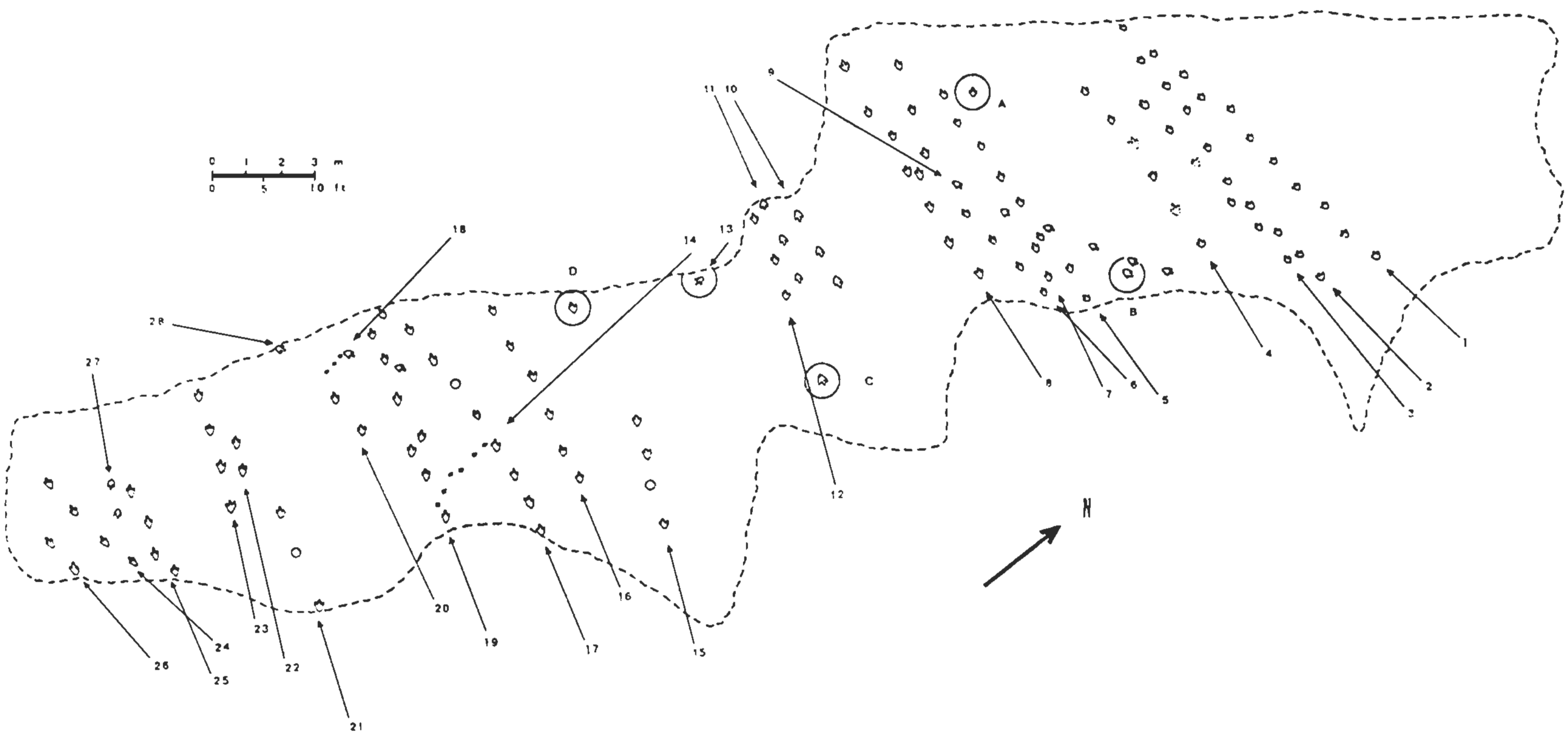


Figure 73. Trackways at Stop 4.5, lower Portland Formation, Holoke, MA.

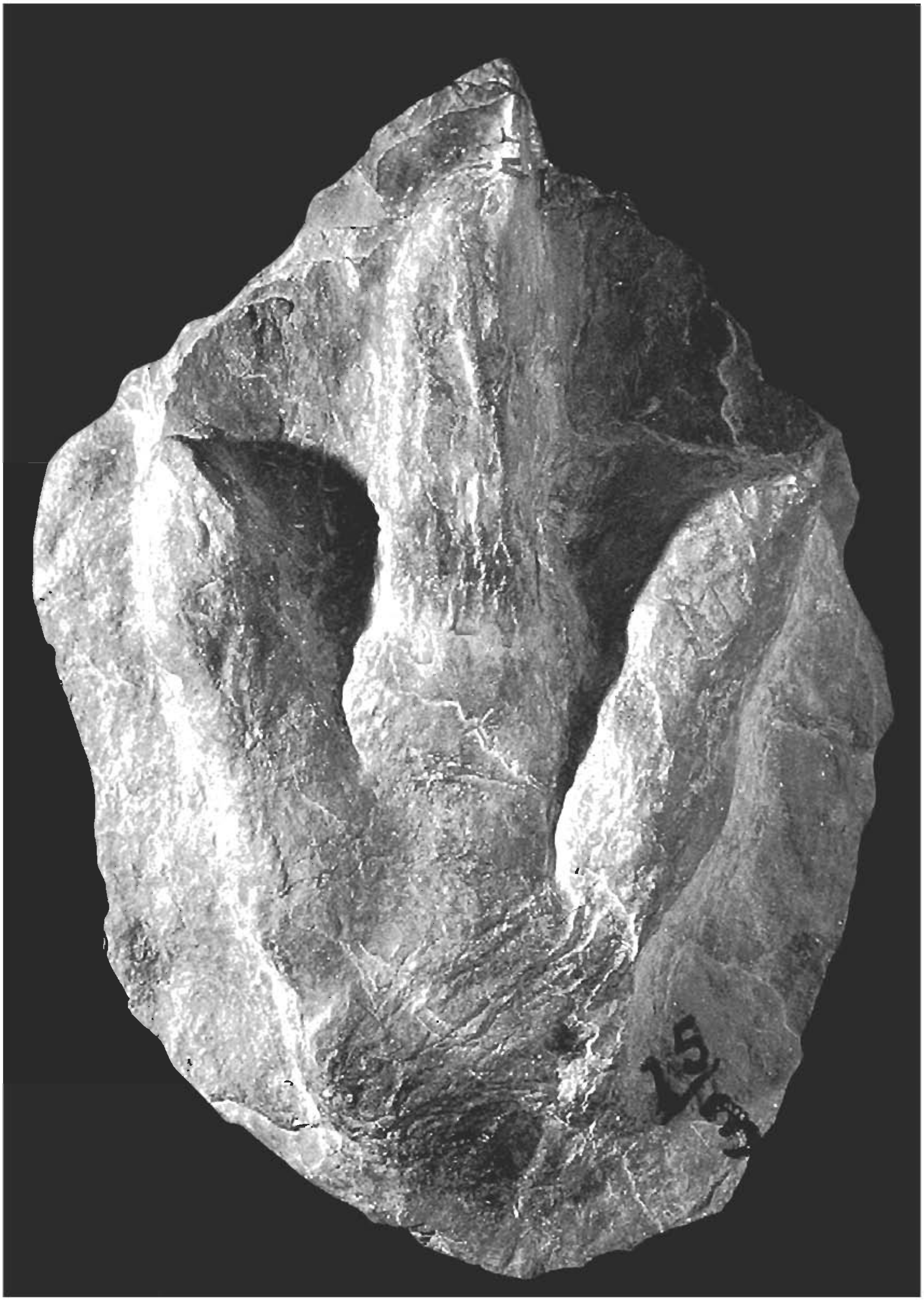


Figure 74. Type of *Eubrontes giganteus*, from Stop 4.5.

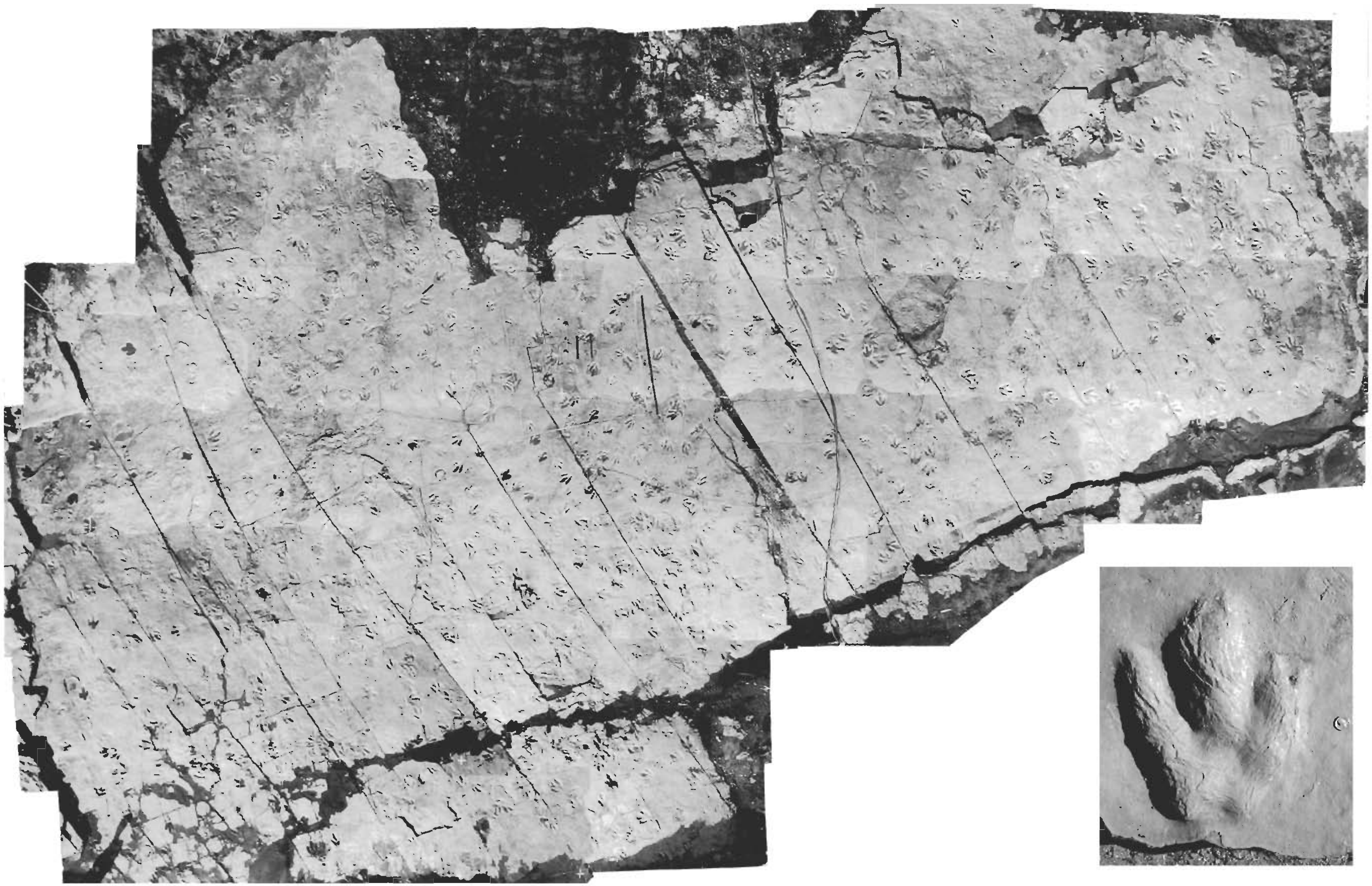


Figure 75. Dinosaur State Park Eubrontes giganteus.

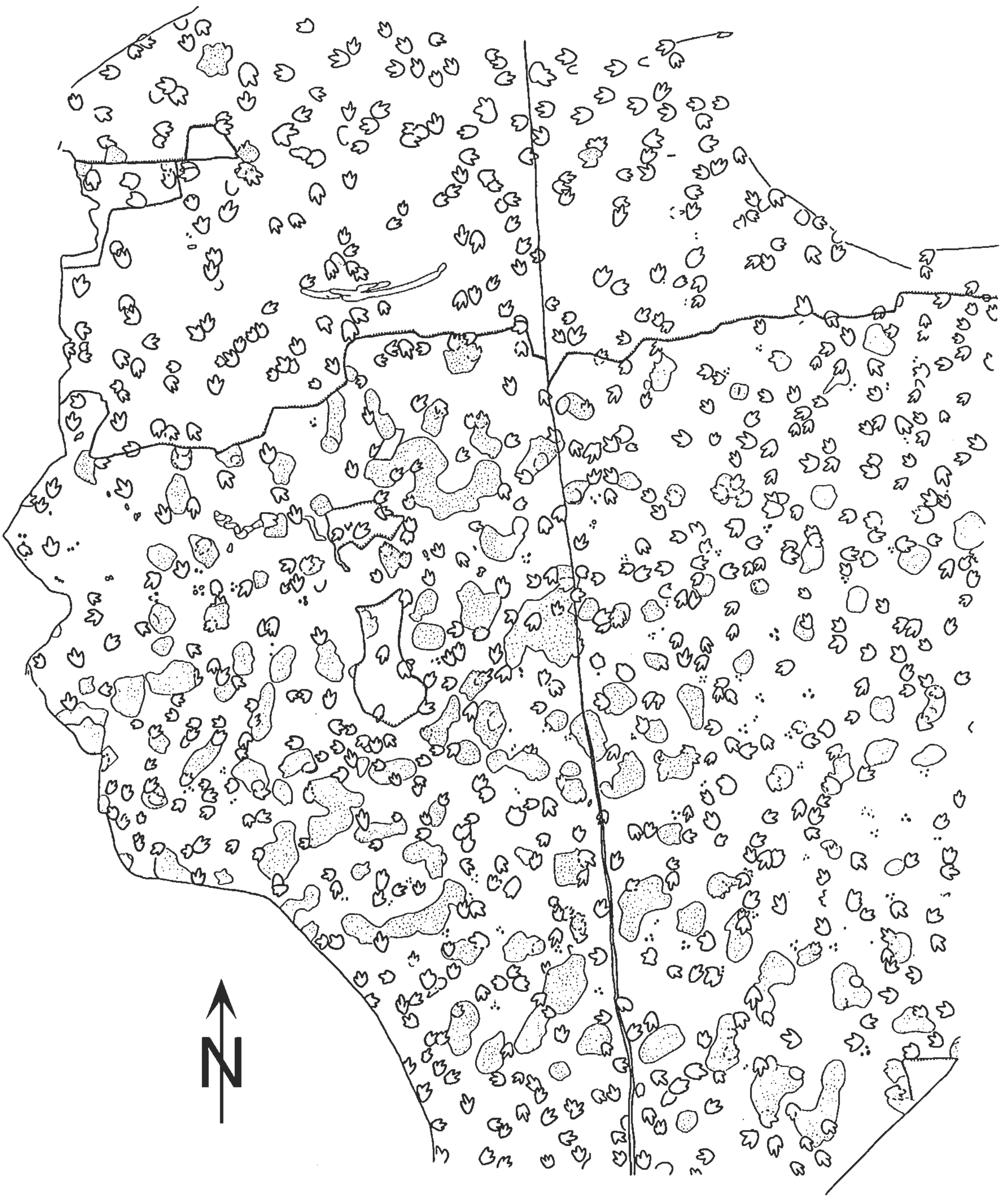


Figure 76. Trackways of *Eubrontes giganteus* at Dinosaur State Park, Stop 4.6.

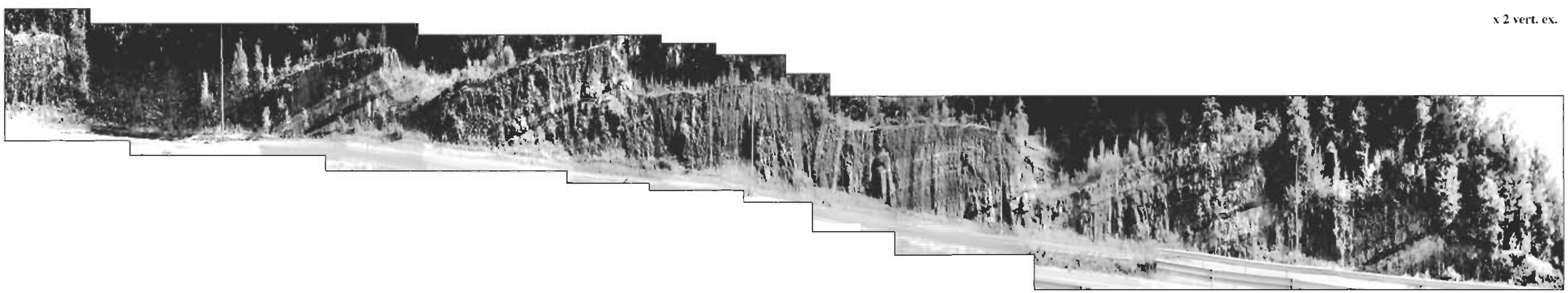


Figure 77. Upper 3/4 of East Berlin Formation exposed at Stop 4.7, Berlin, CT.

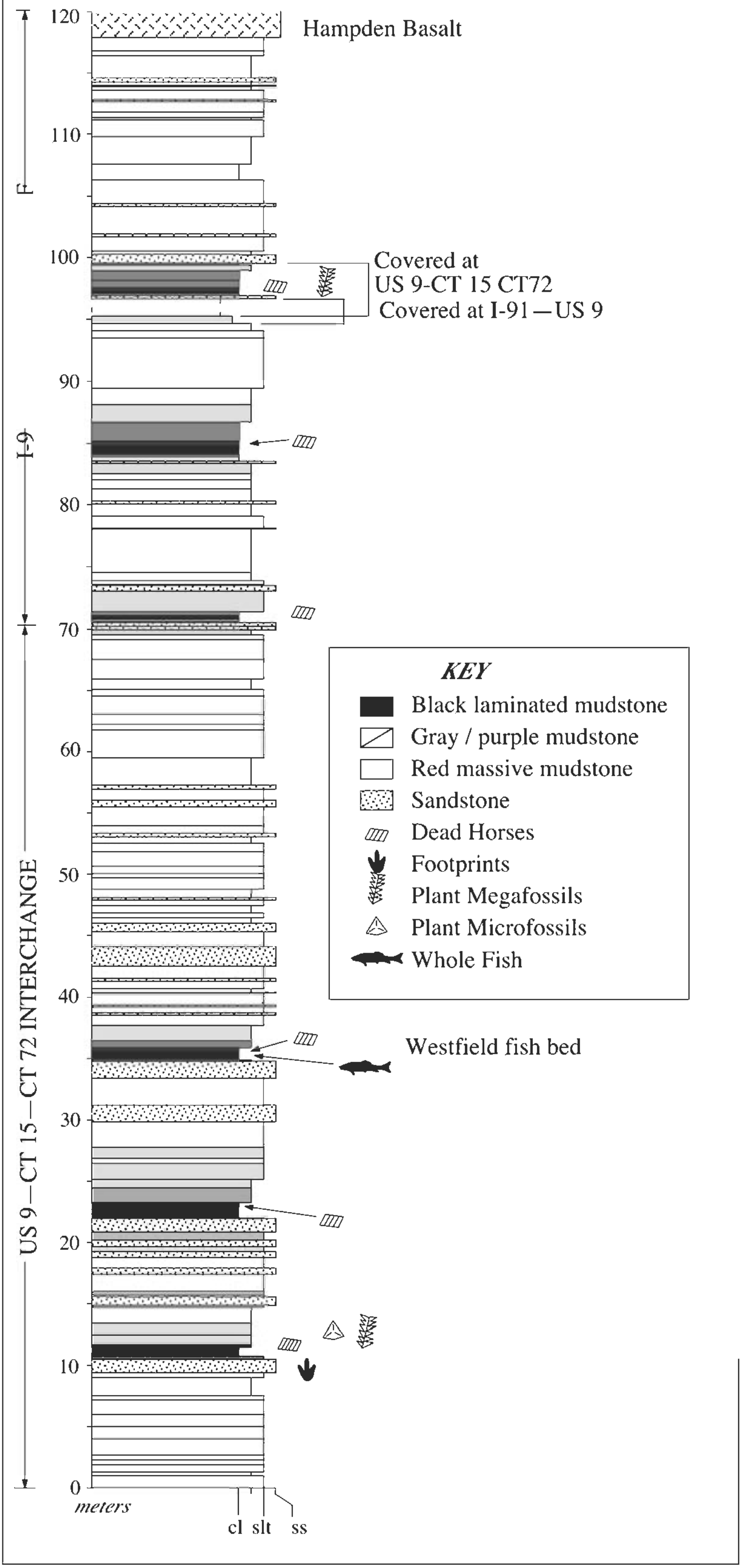


Figure 78. Upper 3/4 of the East Berlin Fm., Stop 4.7.

Silver Ridge, lower Shuttle Meadow Fm.

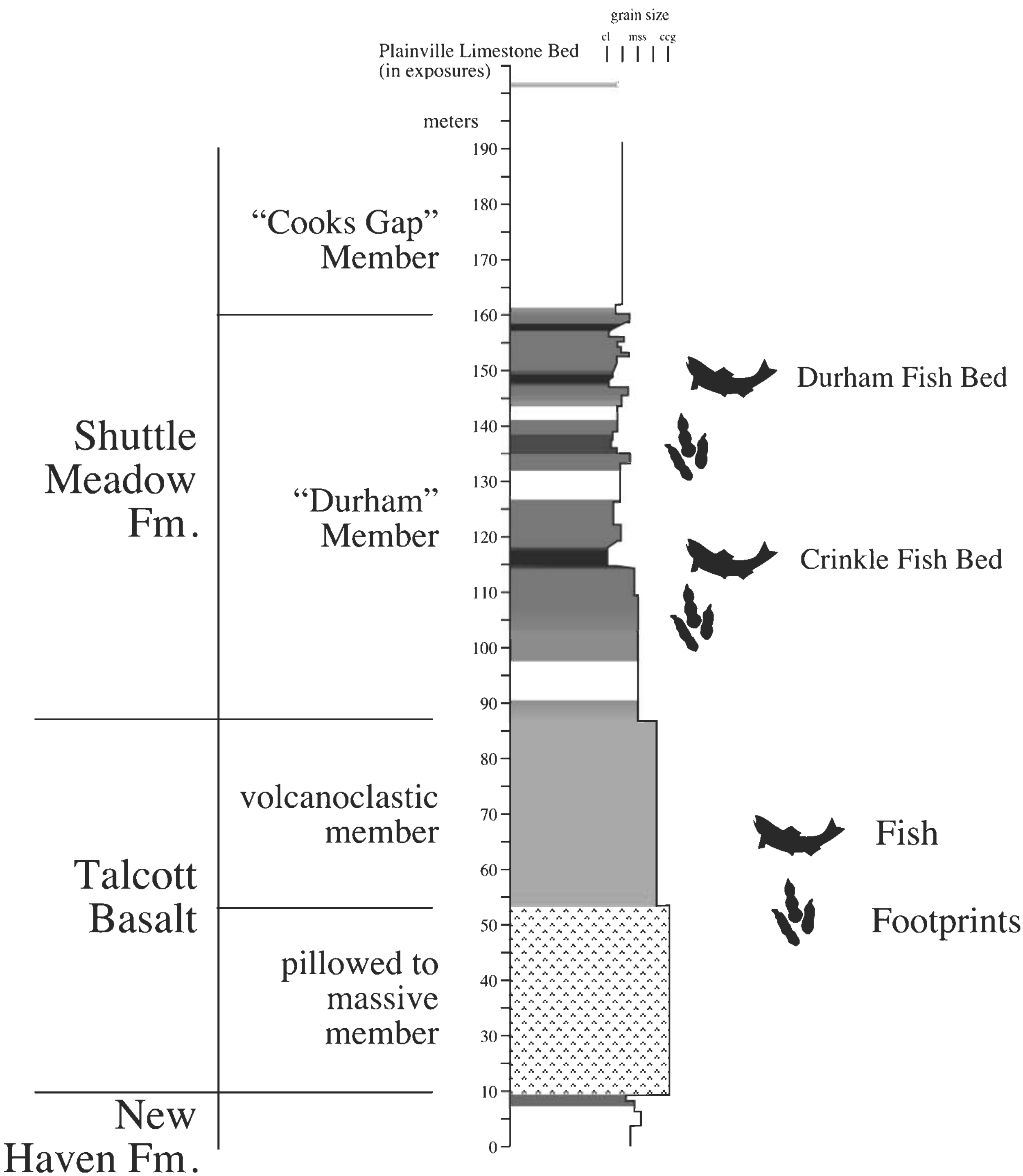


Figure 79