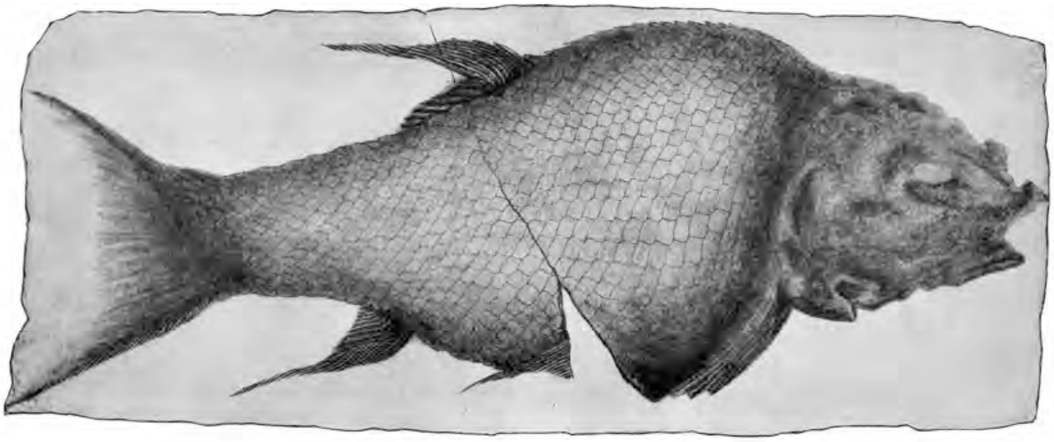
CONTRIBUTIONS TO THE PALEONTOLOGY OF NEW JERSEY (II)

FIELD GUIDE AND PROCEEDINGS

EDITED BY
EMMA C. RAINFORTH
RAMAPO COLLEGE OF NEW JERSEY



GEOLOGICAL ASSOCIATION
OF NEW JERSEY

XXIV ANNUAL CONFERENCE AND FIELD TRIP
OCTOBER 12-13, 2007
EAST STROUDSBURG UNIVERSITY,
EAST STROUDSBURG, PENNSYLVANIA

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TWENTY-FOURTH ANNUAL
CONFERENCE AND FIELD TRIP

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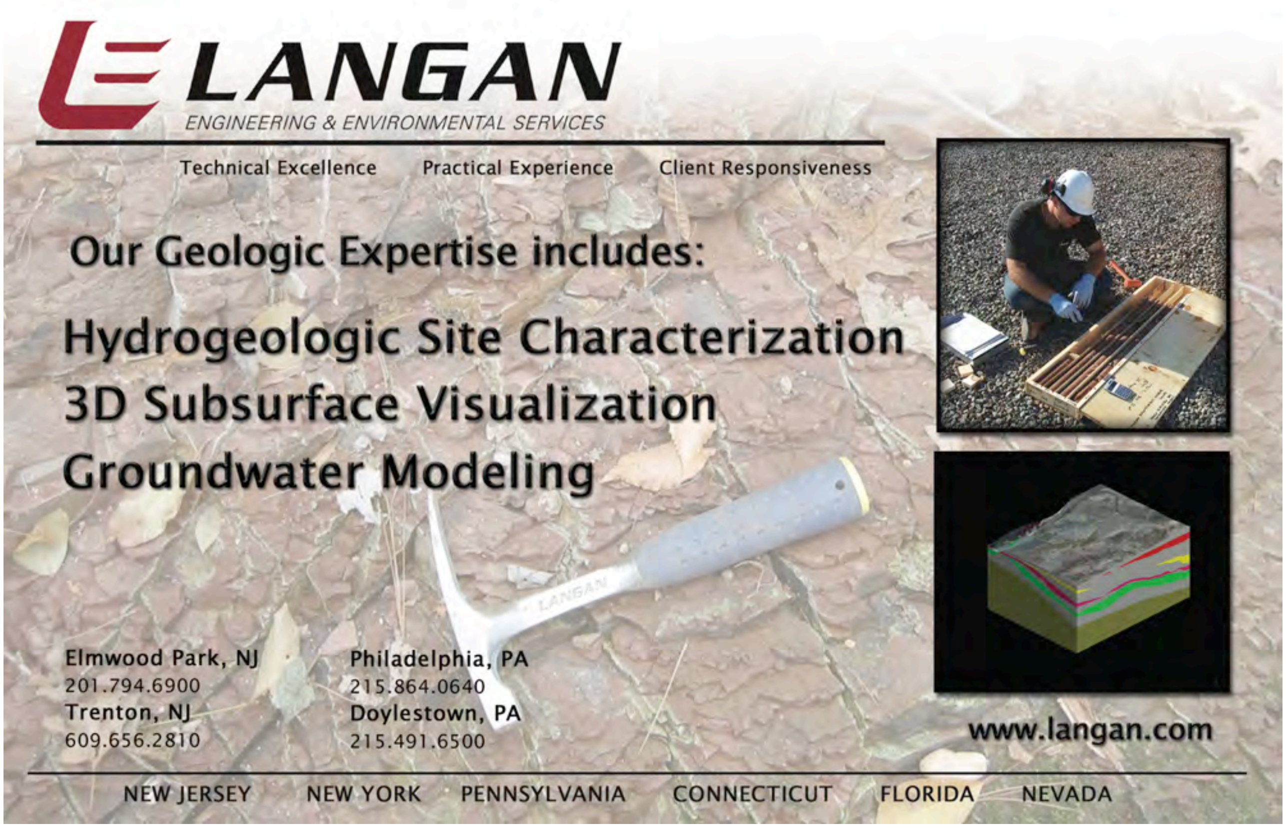

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The Executive Board wishes to thank Dr. Jeffrey Hardy and the Department of Geography at East Stroudsburg University, for hosting GANJ XXIV and providing logistical assistance.

Front cover: *Ischypterus ovatus*, Boonton, N.J. Reproduced from Pl. I, J.S. Newberry 1888, ‘Fossil Fishes and Fossil Plants of the Triassic Rocks of New Jersey and the Connecticut Valley’, U.S. Geological Survey Monograph Vol. 14, 152 p.

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CONFERENCE SCHEDULE

FRIDAY, OCTOBER 12, 2007

Beers Lecture Hall
Registration - 11:00 am to 5:00 pm

Lower Lounge, Dansbury Commons

10:00–1:30	Teacher's Workshop - "Teaching Forensic Geology" – *Nelson Eby, University of Massachusetts-Lowell*

Beers Lecture Hall

1:40–1:50	Welcoming Remarks - *GANJ President Emma C. Rainforth, Ramapo College of New Jersey*
1:50-2:10	Trace fossils from Silurian and Devonian strata at the Delaware Water Gap National Recreation Area, New Jersey – *Robert Metz, Kean University*
2:10-2:30	The Devonian Bivalve, *Archanodon catskillensis*: A Status Report on the First Freshwater Mussel from New Jersey – *John A. Chamberlain, Jr., Brooklyn College*
2:30-2:50	Estimating speeds of dinosaurs from trackways: a re-evaluation of assumptions – *Melissa Manzella, Ramapo College of New Jersey*
2:50-3:10	Ichnotaxonomic updates from the Newark Supergroup - *Emma C. Rainforth, Ramapo College of New Jersey*
3:10-3:30	The Paradox of Large Carcharhinoid-Type Shark Vertebrae in the Upper Cretaceous of New Jersey – *Martin A. Becker, William Paterson University*
3:30-3:50	The Geological Setting, Taphonomy and Paleoecology of a Deltaic Cretaceous (Turonian) Amber-bearing Deposit in Central New Jersey – *Paul C. Nascimbene, American Museum of Natural History*
3:50-4:10	Are Paleozoic Brachiopod Shell Shapes Related to Predation Pressure? A Test of Evolutionary Escalation in Paleozoic Marine Habitats – *William B. Gallagher, New Jersey State Museum*
4:15-5:15	Teacher's Workshop - "The Proposed Fossil Discovery Center and The Sterling Hill Mining Museum Educational Programs: Past, Current and Future" – *James O. Brown, Sterling Hill Mining Museum*
5:15-6:15	Keynote – *Paul E. Olsen, Lamont-Doherty Earth Observatory of Columbia University* – The Triassic-Jurassic Mass Extinction

Lower Lounge, Dansbury Commons

6:30	Banquet and Business Meeting

TABLE OF CONTENTS

PRESENTATION ABSTRACTS

TRACE FOSSILS FROM SILURIAN AND DEVONIAN STRATA AT THE DELAWARE WATER GAP NATIONAL RECREATION AREA, NEW JERSEY

Metz, Robert, Department of Geology and Meteorology, Kean University, Union, New Jersey 07083, rmetz@kean.edu

Marine strata representing deposits of the Silurian Lizard Creek Member (Shawangunk Formation), Upper Silurian Wallpack Center Member (Decker Formation), Lower Devonian Shawnee Island Member (Coeymans Formation), and Lower Devonian Esopus Formation at the Delaware Water Gap National Recreation Area have yielded a variety of trace fossils. Specimens include *Arenicolites* isp., *Arthrophycus alleghaniensis*, *Chondrites* cf. *arbuscula*, *Chondrites affinis*, *Chondrites* isp., *Cruziana* isp., *Diplichnites* isp., *Lockeia siliquaria*, *Monocraterion tentaculatum*, *Palaeophycus herberti*, *Palaeophycus tubularis*, *Planolites beverleyensis*, *Protovirgularia rugosa*, *Protovirgularia* isp., *Rosselia socialis*, *Skolithos linearis*, *Skolithos* ?*pusillus*, and *Skolithos verticalis*. Traces were formed under a variety of environments ranging from shallow to deeper marine conditions, by tracemakers which largely included annelids, arthropods, and bivalves.

THE DEVONIAN BIVALVE, *ARCHANODON CATSKILLENSIS*: A STATUS REPORT ON THE FIRST FRESHWATER MUSSEL FROM NEW JERSEY

Chamberlain, John A., Jr., Department of Geology, Brooklyn College, Brooklyn, NY 11210 *and* Doctoral Program in Earth and Environmental Sciences, Graduate Center of the City University of New York, New York, NY 10016, johnc@brooklyn.cuny.edu
Chamberlain, Rebecca B., Department of Biology, College of Staten Island, Staten Island, NY 10314, Chamberlain@mail.csi.cuny.edu

Archanodon catskillensis is a member of the oldest known genus of freshwater bivalves. Although the main occurrences of this species are in New York and Pennsylvania, its burrows are known from the Bellvale Sandstone (Givetian) of northern New Jersey. *A. catskillensis* has two shell morphs, each of which may be a separate species. *A. catskillensis* also differs from *A. westoni*, the other North American *Archanodon* species. *A. catskillensis* is the most common macroinvertebrate in non-marine facies of the Devonian Catskill clastic wedge, where it is found in channel fill and overbank deposits. *A. catskillensis* is an erect, semi-infaunal filter-feeder which often lived in clusters of many individuals. Its life habits thus appear very similar to those of many modern unionoid bivalves. Organic adventitious layers appear to be present in the shell microarchitecture of *A. catskillensis*. These points, together with its abundance and wide distribution in Catskill rocks, strongly implies that the genus should be included in the bivalve order Unionida. Disparities in shell form among *Archanodon* species indicate that taxonomic revision of the genus may eventually be necessary.

ESTIMATING SPEEDS OF DINOSAURS FROM TRACKWAYS: A RE-EVALUATION OF ASSUMPTIONS

Rainforth, Emma C., and Manzella, Melissa, Environmental Science, Ramapo College of New Jersey, 505 Ramapo Valley Road, Mahwah, NJ 07430; erainfor@ramapo.edu, mmanzell@ramapo.edu

For 30 years, using equations determined by Alexander (1976), paleontologists have estimated speeds of dinosaurs from their trackways; the fundamental assumption, based on limited observations, was that dinosaur hip height is approximately four times foot length. Thulborn (1990) subsequently determined that the leg length to foot length ratio ranges from 4.5-6.0, according to type and size of dinosaur. Given that the focus of many published footprint studies is to estimate dinosaur speed from Alexander's equations, it is critical that the hip height of the track maker can be ascertained from the footprint measurement. If there is high variability in the ratio of hip height:foot length within a group of dinosaurs, speed estimates are going to be extremely unreliable.

This study examined the relationship between foot length and leg length in a variety of dinosaurs. Measurements of 24 dinosaur specimens included ornithischians (bipedal and quadrupedal), theropods, dinosauriforms, birds, and sauropods. Leg length was defined as femur + tibia + metatarsal III; foot length was defined as that part of the foot preserved in footprints (digit III phalanges ± claw + metatarsal III – metatarsal IV). Leg and foot lengths were compared and it was found that in bipedal ornithischians the foot to leg length ratio is ~5.4-5.9, and in theropods, 2.8-4.2. Contrary to previous studies, we found that (1) there is no correlation between dinosaur size and foot to leg length ratio, (2) the foot to leg length ratio is greater than previously estimated, and (3) the foot to leg length ratio is highly variable for each group of dinosaurs. We conclude that estimating dinosaur speed from trackways should not be undertaken lightly, and the results be interpreted with caution.

ICHNOTAXONOMIC UPDATES FROM THE NEWARK SUPERGROUP

Rainforth, Emma C., Environmental Science, Ramapo College of New Jersey, 505 Ramapo Valley Road, Mahwah, NJ 07430; erainfor@ramapo.edu

The Newark Supergroup (Late Triassic – Early Jurassic) of eastern North America is world-famous for it's fossil footprint assemblages. Footprints are the most common tetrapod fossils from these strata. The field of ichnology owes it's existence to the pioneering work of Edward Hitchcock who, beginning in the 1830s, named and described Newark Supergroup footprints from the Connecticut Valley (Hartford and Deerfield basins), primarily from the Early Jurassic strata. These footprints are dominantly dinosaurian in origin, including several ichnogenera attributable to theropods. Subsequent studies elsewhere in the Supergroup have resulted in a few additional ichnogenera and ichnospecies being discovered, including *Apatopus* and *Brachychirotherium* from Milford, NJ. Whilst the nomenclature of the Connecticut Valley prints has been addressed (Rainforth 2005), the ichnotaxonomy (relationships between footprints) has not been revised in detail. It is recommended here that not only the synonymy of *Grallator* and *Anchisauripus* with *Eubrontes* be upheld, but in addition, the remaining prints from the Connecticut Valley attributed to theropods should also be synonymized with *Eubrontes* because they are only behaviorally (rather than osteologically) distinct. Examination of two ichnogenera attributed to crurotarsans have also resulted in nomenclatural and ichnotaxonomic revisions. Some of Hitchcock's ichnospecies of *Batrachopus* are synonymized; *Shepardia* and *Comptichnus* are synonymized with *Batrachopus*; and Lockley *et al.'s* (2004) synonymization of *Selenichnus* with *Batrachopus* is rejected. *Apatopus* is found to only occur at one location in the Newark Supergroup (Milford NJ); specimens from other localities and stratigraphic horizons were mis-identified and are brachychirotheres.

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Rainforth, E.C. 2005. Ichnotaxonomy of the fossil footprints of the Connecticut Valley (Early Jurassic, Newark Supergroup, Connecticut and Massachusetts). *Ph.D. thesis, Columbia University, 1302 pp.*

THE PARADOX OF LARGE CARCHARHINOID-TYPE SHARK VERTEBRAE IN THE UPPER CRETACEOUS OF NEW JERSEY

Becker, Martin A., Department of Environmental Science, William Paterson University, Wayne, NJ 07470; beckerm2@wpunj.edu
Chamberlain, Rebecca B., Department of Biology, College of Staten Island Staten Island, NY 10314; chamberlain@mail.csi.cuny.edu
Chamberlain, John A., Jr., Department of Geology, Brooklyn College and Doctoral Program in Earth and Environmental Sciences CUNY Graduate Center, New York, NY 10016; johnc@brooklyn.cuny.edu

Carcharhiniform and lamniform sharks are thought to derive from a common ancestral galeomorph during the Middle Mesozoic. Isolated carcharhinoid-type vertebrae found in the upper Cretaceous of New Jersey preserve anatomical characteristics, namely solid centra, analogous to vertebrae found in Cenozoic and modern carcharhiniforms. Conservative estimates of size based on total body length-centrum radius or diameter regressions for fossil and modern carcharhiniforms and lamniforms indicates that some of these Upper Cretaceous sharks with carcharhinoid-type vertebrae may have achieved total lengths of five meters or more. Paradoxically, a rich fossil record of shark teeth from the Upper Cretaceous of New Jersey and elsewhere in North America lacks any firm evidence for large-bodied ancestral carcharhiniforms. Although large lamniforms have left an abundant tooth record in the New Jersey Upper Cretaceous, the North American carcharhiniform tooth record is one of small-bodied genera (e.g., *Galeorhinus*, *Palaeogaleus*) unlikely to have possessed such large carcharhinoid-type vertebrae. However, one extinct family of large Upper Cretaceous lamniform sharks, the Anacoracidae, contains species with both lamniform teeth and carcharhinoid-type vertebral morphology. In New Jersey, two well-known anacoracids, *Squalicorax kaupi* and *Squalicorax pristodontus* co-occur in the same stratigraphic horizons as the large, isolated carcharhinoid-type vertebrae and represent the most-likely species for the origin of these vertebrae. Extinction across the Cretaceous-Tertiary boundary of large lamniforms with carcharhinoid-type vertebrae may explain the absence of this shared anatomical characteristic during the Cenozoic.

THE GEOLOGICAL SETTING, TAPHONOMY AND PALEOECOLOGY OF A DELTAIC CRETACEOUS (TURONIAN) AMBER-BEARING DEPOSIT IN CENTRAL NEW JERSEY

Nascimbene, Paul C., Paleoentomological Collections, Division of Invertebrate Zoology, American Museum of Natural History, New York NY; nash@amnh.org

A spectacular and diverse assemblage of fossil plants, arthropods and other organisms has been recovered from amber contained in or near lignitic lenses, in an exposure of the Raritan Formation at Crossman's Pit, Sayreville, NJ (Grimaldi, et al, 2000). Significant finds have included early flowers, primitive ants, feathers, and the oldest Tardigrade, among others. The amber appears to be primarily from two species of Cupressaceae (Anderson, K. B., 2006), and there is evidence for low-energy transport, such that the resin-producing forest was probably close to the ancient deltas where vegetation and resin were deposited. The clays at this site have themselves yielded many tiny fusinized flowers (Gandolfo, Nixon and Crepet, 2004, 2002, 1998), as well as leaf impressions. The Atlantic Coastal Plain has undergone little geological activity since the rifting apart of Africa from North America at the end of the Triassic. Thus, the nearshore clay, sand and lignite layers at this site have been exposed to relatively little overburden pressure or other geothermal effects, and have remained as unconsolidated paleosols. Physical properties of amber from this and other Atlantic coastal sites were tested against other Cretaceous ambers (Nascimbene, et al, in preparation), and the results showed that these ambers are softer than typical Class I ambers for their age, possibly due (at least in part) to a 'relaxed' geological setting, in which slower-than-usual thermal maturation has occurred.

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ARE PALEOZOIC BRACHIOPOD SHELL SHAPES RELATED TO PREDATION PRESSURE? A TEST OF EVOLUTIONARY ESCALATION IN PALEOZOIC MARINE HABITATS

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Vermeij and others have postulated changes in the shell shape of benthic mollusks as a response to increasingly effective predators, especially during the later Mesozoic. This escalatory response should be observable elsewhere in different phyla of benthos. Investigations of shell shape in Paleozoic brachiopods might substantiate a general pattern of escalation. One measure of predation resistance is shell convexity; inflated shells withstand cracking stresses better than flat shells, given equal thicknesses. Measurements of several classes of brachiopods shell shapes for convexity ratios through the Paleozoic from the Ordovician to the Permian show no clear trend of convexity increase except for the strophomenid brachiopods, which clearly show an increase from flat shelled to globose. This could also be attributed in terms of a habitat shift from softer sea bottom environments earlier in the Paleozoic to harder substrates in the reef environments of the later Paleozoic.

Another aspect of shell shape that has been cited as a potentially predation resistant feature is the presence of interlocking zigzag commissures. This was supposed to exclude predators such as asteroids, which feed by everting their stomachs into gapes in the commissures of shelled benthos. Predatory asteroids have been present since the Ordovician. Laboratory aquarium experiments on models of shelled benthos show no differential feeding preference by asteroids of one species (*Asterias forbesi)* on smooth margined commissures as opposed to zigzag commissures.

It is interesting to note that most surviving brachiopods either have an inflated shell shape (terebratulids) or a tightly zigzag commissure (rhynchonellids), so some other selective mechanism may be at work.

THE TRIASSIC-JURASSIC MASS EXTINCTION

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Generally regarded as one the "big five" mass extinction events of the Phanerozoic, that at the close of the Triassic marks the transition into the true age of the dinosaurs. Recent discoveries over the last decade show that in the continental realm tetrapod diversity was increasing through the Triassic, culminating sometime close to, if not at, the onset of the extinction event. Various non-dinosaurian archosaur groups became remarkably dinosaur-like with both carnivorous and herbivorous forms living side by side with their dinosaurian competitors for millions of years. Several more bizarre and unfamiliar tetrapod groups were diversifying at the same time, with the whole assemblage showing the kind of structural diversity not seen again until the Cretaceous over 55 million years later. There was also geographic diversity, with very different communities in different zonal climate belts, despite the fact a single individual archosaur theoretically could have walked from Brisbane to Vladivostok across the supercontinent. This taxonomic and biogeographic diversity ended at the end of the Triassic, very close in time to the eruption of the largest known flood basalt event, the Central Atlantic Magmatic Province (CAMP), although it is far from clear whether these lavas or some other event, such as an asteroid impact, caused the diversity drop. Whatever the cause, based on sections where paleobiological data can be traced continuously across the boundary, the diversity decline was abrupt. Among continental tetrapods, the decline was catastrophic, with a wipe out of nearly all but currently extant major groups including all potential dinosaur-competitors except crocodylomorphs. Early Jurassic land tetrapod assemblages were thus of very low diversity at the family and higher taxonomic levels, and strangely biased towards carnivores. Included were abundant, and possibly diverse at the species level, large and small theropod dinosaurs with features strongly suggesting piscivory, suggesting that surviving tetrapod communities had largely water-based economies. These were the makers of the familiar brontozoid tracks, such as the famous *Eubrontes* so common in Early Jurassic footprint assemblages. Nonetheless, although these survivors largely founded the modern world, it took tens of millions of years for "normal" looking land-plant-based tetrapod communities to re-evolve, with large herbivores finally becoming common by the close of the Early Jurassic.

TECHNICAL PAPERS

TRACE FOSSILS FROM SILURIAN AND DEVONIAN STRATA AT THE DELAWARE WATER GAP NATIONAL RECREATION AREA, NEW JERSEY

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ABSTRACT

Marine strata representing deposits of the Silurian Lizard Creek Member (Shawangunk Formation), Upper Silurian Wallpack Center Member (Decker Formation), Lower Devonian Shawnee Island Member (Coeymans Formation), and Lower Devonian Esopus Formation at the Delaware Water Gap National Recreation Area have yielded a variety of trace fossils. Specimens include *Arenicolites* isp., *Arthrophycus alleghaniensis*, *Chondrites* cf. *arbuscula*, *Chondrites affinis*, *Chondrites* isp., *Cruziana* isp., *Diplichnites* isp., *Lockeia siliquaria*, *Monocraterion tentaculatum*, *Palaeophycus herberti*, *Palaeophycus tubularis*, *Planolites beverleyensis*, *Protovirgularia rugosa*, *Protovirgularia* isp., *Rosselia socialis*, *Skolithos linearis*, *Skolithos* ?*pusillus*, and *Skolithos verticalis*. Traces were formed under a variety of environments ranging from shallow to deeper marine conditions, by tracemakers which largely included annelids, arthropods, and bivalves.

INTRODUCTION AND GEOLOGIC SETTING

Silurian and Devonian rocks are exposed within the boundaries of the Delaware Water Gap National Recreation Area of northwestern New Jersey and adjacent northeastern Pennsylvania. Though these rocks have been extensively studied and debated (e.g., Rogers, 1858; Weller, 1900; Epstein et al., 1967; Spink, 1967; Epstein, 1970; Barnett, 1970; Epstein and Epstein, 1972), detailed trace fossil studies have been largely neglected (e.g., Martino and Zapecza, 1978), a factor that the author has attempted to address (Metz, 1998a, 1998b, 2003a, 2003b), as well as continuing field work. This paper documents a compilation of trace fossils found, thus far, at the DWGNRA, as well as providing the details of their likely paleoenvironment.

The Silurian Lizard Creek Member (Shawangunk Formation) consists of light- to dark-gray interbedded sandstones, siltstones, and shale representing marginal marine deposits formed during a transgressive phase (e.g., Epstein and Epstein, 1972). Upper Silurian Wallpack Center Member (Decker Formation) deposits consist of sporadically fossiliferous, light- to medium-gray calcareous sandstones, and fossiliferous, medium- to medium-dark-gray quartzose limestones and siltstones, representing shallow marine deposits (e.g., Epstein et al., 1967). The interbiohermal facies of the Shawnee Island Member of the Coeymans Formation (Lower Devonian) consists of sporadically fossiliferous, medium-gray to medium-dark-gray argillaceous and arenaceous limestones formed in a low to moderate energy shallow-water, sub-tidal environment subject to periodic high-energy conditions (e.g., Epstein et al., 1967; Spink, 1967). Strata of the Lower Devonian Esopus Formation include medium- to dark-gray finely arenaceous to shaly siltstone, with calcareous siltstone occurring near the top of the unit. The formation is considered to have formed under deep neritic conditions (e.g., Epstein, 1984).

SYSTEMATIC ICHNOLOGY

Ichnogenus *Arenicolites* Salter, 1857
***Arenicolites* isp.**
Figure 1A

Description: Vertical to slightly oblique U-shaped burrows, some multiple or branched specimens, preserved in full relief. The arms of the U are parallel as well as non-parallel. Burrows are unlined and filled with darker, finer-grained sediment than the host rock. Burrows are 1-5 mm in diameter, spaced 0.5-3.0 cm apart, commonly exhibit flared trumpet-shaped apertures 3-8 mm in diameter, and extend down to 4 cm in depth.
Remarks: The multiple or branched nature and apparent lack of a wall lining in *Arenicolites* suggest that the burrows do not represent a permanent domicile (*sensu* Dam, 1990). *Arenicolites* is interpreted to represent the dwelling and feeding structure of suspension- [possibly, partial deposit-] feeding (Eagar et al., 1985)] worms or worm-like forms (Hakes, 1976; Miller, 1979; Dam, 1990), crustacean-like organisms (Goldring, 1962), or invertebrates (Eagar et al., 1985).
Environmental distribution: *Arenicolites*, the most abundant trace fossil present in the Lizard Creek Member (Shawangunk Formation), inhabited a variety of marginal marine environments. These include beach or bar deposits associated with tidal flats, and tidal-gulley and tidal-channel deposits (also, see Epstein and Epstein, 1972).

Ichnogenus *Arthrophycus* Hall, 1852
***Arthrophycus alleghaniensis* (Harlan, 1931)**
Figure 1B

Description: Straight to curved, horizontal to sub-horizontal, single or bundled burrows, 4-9 mm in diameter, up to a maximum length of 13 cm. Trace fossils commonly branch, have vertical relief up to 6 mm, and a few exhibit tapering ends. Many burrows exhibit closely spaced transverse annulations (5-9 per cm), in others these are indistinct or absent. A few specimens bear a faint narrow, central longitudinal furrow. Burrow fill is structureless and similar to the host rock.
Remarks: Diameters of previous described specimens of *Arthrophycus* range from 1 mm to 2.5 cm (Książkiewicz, 1977; Baldwin, 1977). The present specimens are similar in form and size to those illustrated by Baldwin (1977), Pickerill et al. (1984), and Legg (1985). *Arthrophycus* is inferred to represent the feeding burrow of an annelid or arthropod (e.g., Schuchert, 1916), and has only been recorded from marine deposits.
Environmental distribution: *Arthrophycus*, found in the Lizard Creek Member, likely inhabited bar or beach areas associated with tidal flats (Epstein and Epstein, 1972).

Ichnogenus *Chondrites* von Sternberg, 1833
***Chondrites* cf. *arbuscula* Fischer-Ooster, 1858**
Figure 1C

Description: A dendritic pattern of slightly curved to straight burrows, 1-2 mm in diameter, 2-10 mm long, lying parallel to stratification as well as being present on vertical surfaces. Individual burrows do not curve back, cross on themselves, or interpenetrate. Burrows are ellipsoidal or circular in cross-section, and 1.0-1.5 mm in diameter. Branching angles are acute, 35°-60°. Branching mostly second-order; burrow fill darker in color and finer in grain size than the surrounding rock.

Remarks: The specimens compare favorably to *Chondrites* type-B of Osgood (1970) and *Chondrites arbuscula* of Książkiewicz (1977). The ichnologic classification of *Chondrites* uses the branch width and angle, as well mode of branching, and as such has resulted in more than 170 ichnospecies being described (Han and Pickerill, 1994), many, in fact may reflect ontogenetic variation (Książkiewicz, 1977). Interpreted as both a feeding- and dwelling-burrow, suggested tracemakers include worms or worm-like forms (e.g., Osgood, 1970; Fu, 1991), and arthropods (Ekdale, 1977). Recently Seilacher (1990) and Fu (1991) suggested that *Chondrites* is a chemosymbiont, supplying sulfide-oxidizing bacteria with oxygen.
Environmental distribution: Interpreting *Chondrites* may be difficult since it is known to occur in different rock types representing a variety of depositional environments. Within the Lizard Creek Member, *Chondrites* cf. *arbuscula* likely represents deep-tier inhabitation beneath a fully oxygenated seafloor.

Ichnogenus *Chondrites* von Sternberg, 1833
Chondrites affinis (Brongniart, 1849)
Figure 1D

Description: Slightly curved to straight bedding plane specimens exhibiting no evidence in vertical section. Burrow diameter (2-5 mm) not constant throughout, which tends to increase in width toward distinctive rounded endings; maximum length up to 5 cm. Second-order branching, branching angles acute (25°-55°), burrow fill finer and darker than the surrounding rock.
Remarks: The specimens compare very favorably to *Chondrites affinis* of Książkiewicz (1977).
Environmental distribution: *Chondrites affinis* is found within the Lower Devonian Shawnee Island Member (Coeymans Formation), with inhabitation likely similar to *C.* cf. *arbuscula*.

Ichnogenus *Cruziana* d'Orbigny 1842
Cruziana isp.
Figure 1E

Description: Straight to slightly curved, somewhat poorly preserved trace. Trace is 2 mm wide and 15 mm long, and composed of two low-relief symmetrical lobes (0.75-1 mm wide), separated by a shallow median furrow. There is faint evidence of transverse scratch marks occurring at irregular intervals along the lobes.
Remarks: Following the recommendations of Keighley and Pickerill (1996), concerning problems associated with small bilobate trails, the presence of transverse scratchmarks and a 'length-width' ratio of more than 2:1, allows the specimen to be assigned to *Cruziana*. Nonetheless, poor preservation of the scratchmarks precludes further ichnospecific assignment. Trilobites are commonly cited as the producers of *Cruziana* (e.g., Seilacher, 1970).
Environmental distribution: *Cruziana* is found in shallow marine deposits of the Upper Silurian Wallpack Center Member (Decker Formation), with tracemaking occurring during moderate to low energy shallow marine conditions, punctuated by periodic, higher energy (likely storm) conditions.

Ichnogenus *Diplichnites* Dawson, 1873
Diplichnites isp.
Figure 1F

Description: Straight trackway, up to 17 mm in length, consisting of triangular impressions, bilateral, but slightly offset from each other. Imprints are spaced 3-7 mm apart and range up to 6 mm in length. Internal

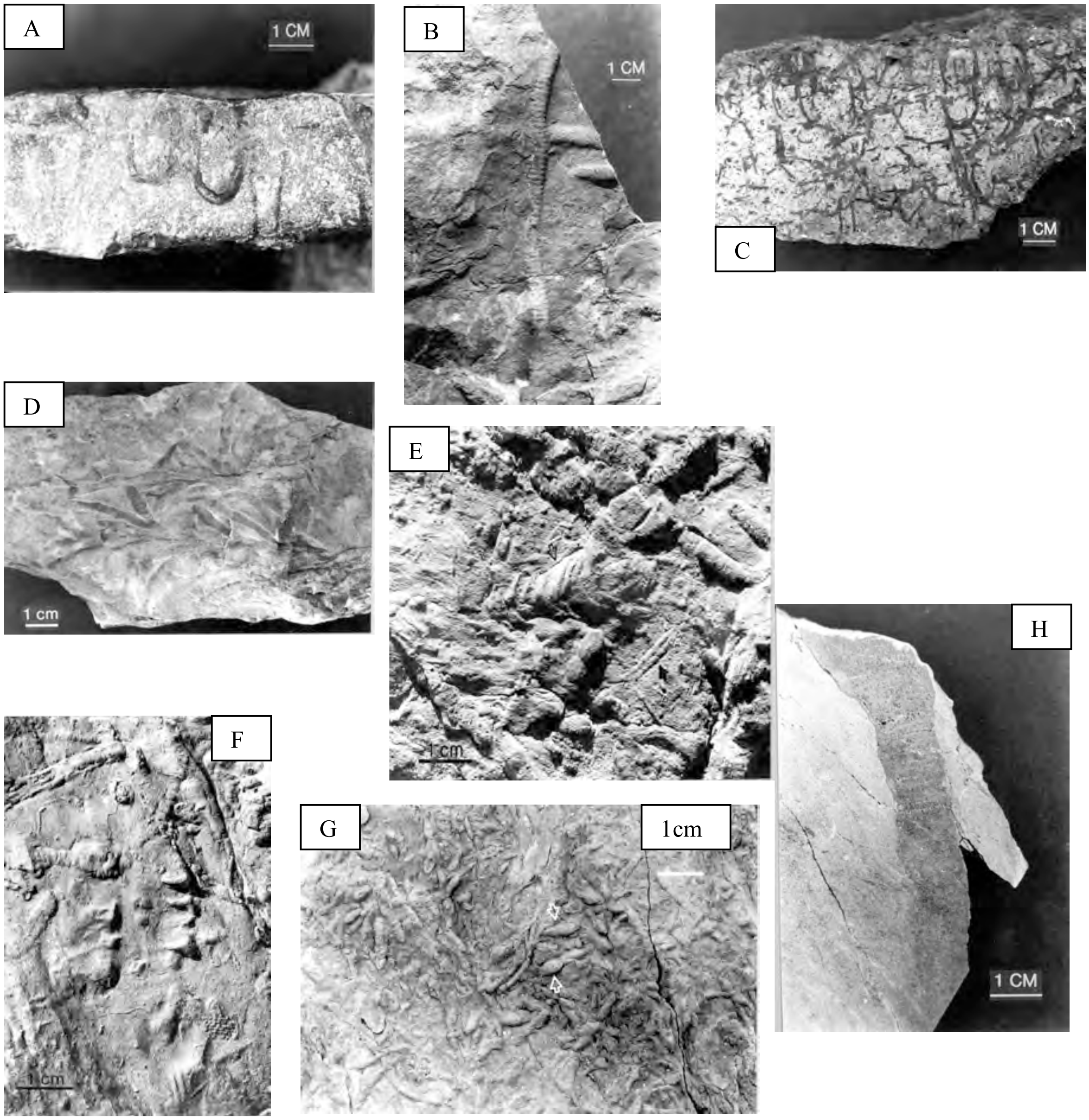

Figure 1. Trace fossils from the Delaware Water Gap National Recreation Area. (A) *Arenicolites* isp. in vertical section exhibiting flared trumpet-like apertures. (B) *Arthrophycus alleghanienis* preserved on sandstone sole. (C) *Chondrites* cf. *arbuscula* in vertical section. (D) *Chondrites affinis* preserved on bedding plane. (E) *Cruziana* isp. (closed arrow) as well as *Protovirgularia* isp. (open arrow). (F) *Diplichnites* isp. (G) *Lockeia siliquaria* (arrows). (H) *Monocraterion tentaculatum* on cut slab, collected from folded portion accounting for distortion of trace. After Metz, 1998a, 2003a, 2003b.

width of trackway is 9-11 mm, maximum external width is 22 mm. A linear set of circular to ?bilateral impressions is located midway between the paired triangular impressions. Thin marks, about 4 mm in length, extend laterally from two of the triangular impressions.
Remarks: Due to the insufficient length of the trackway, and distinctive midpoint impressions, the specimen is left in open ichnospecific nomenclature. *Diplichnites* is envisioned to represent an arthropod locomotion trace, most often attributed to trilobites (e.g., Pickerill et al., 1984). However, this trackway bears a remarkable similarity to an Ordovician (Johnson et al., 1994) as well as a Silurian specimen (Easterday and Babcock, 1999), both of which have been attributed to a myriapod-like arthropod. As such, a myriapod was the most likely tracemaker of the present specimen.
Environmental distribution: *Diplichnites* is present in the Wallpack Center Member, and was produced under conditions similar to *Cruziana*.

Ichnogenus *Lockeia* James, 1879
***Lockeia siliquaria* James, 1879**
Figure 1G

Description: Almond- to near oval-shaped structures (width 2-5 mm, 3-10 mm in length), typically with smooth surfaces lacking ornamentation, although some specimens exhibit wrinkles.
Remarks: Most researchers have cited bivalves as likely producer of *Lockeia* (e.g., Mángano et al., 1998), while a few have noted branchiopod crustaceans (e.g., Pollard, 1981). Since bivalves have been documented from the Decker Formation, they are the likely producers.
Environmental distribution: *Lockeia* is found in the Wallpack Center Member, and was produced under conditions similar to *Cruziana*.

Ichnogenus *Monocraterion* Torell, 1870
***Monocraterion tentaculatum* Torell, 1870**
Figure 1H

Description: Circular to ellipsoidal funnels, 3 cm in height, up to 5 cm in diameter, pierced by straight to slightly curved, sand filled tubes, up to 25 cm in length, 2-5 mm in diameter, perpendicular to bedding surfaces. Rare funnels exhibit concentric, alternating dark and light laminae surrounding the central tube.
Remarks: *Monocraterion* is considered to be a dwelling structure formed by a worm-like, possibly polychaete form (e.g., Barwis, 1985).
Environmental distribution: Found in the Lizard Creek Member, evidence points to a relatively high energy environment (e.g., Fürsich, 1975), which is interpreted to be represented by intertidal to shallow subtidal conditions.

Ichnogenus *Palaeophycus* Hall, 1847
***Palaeophycus heberti* Saporta, 1872**
Figure 2A

Description: Straight to slightly curved, unbranched, horizontal, smooth, thickly lined full relief burrows exhibiting partial collapse. Maximum preserved length 40 cm, wall linings dominantly 2-4 mm thick, variable burrow diameter in many specimens (overall range 4-12 mm). Burrow fill is structureless and similar to the host rock; sediment of wall lining lighter in color than host rock. Burrow crossovers are present.
Remarks: The presence of distinctive “thick” wall linings in all specimens allows assignment to *P.*

heberti. *Palaeophycus* has been documented from marine (e.g., Frey and Howard, 1970), and nonmarine settings (e.g., Buatois and Mángano, 1993). Suggested producers include suspension feeding or predaceous organisms (Pemberton and Frey, 1982), worm-like forms (Miller, 1993), as well as insects and other arthropods in other settings (Buatois and Mángano, 1993).
Environmental distribution: *Palaeophycus heberti* is present in the Wallpack Center Member, formed under conditions similar to *Cruziana*.

Ichnogenus *Palaeophycus* Hall, 1847
***Palaeophycus tubularis* Hall 1847**
Figure 2B

Description: Straight to curved, cylindrical to ellipsoidal, unornamented, horizontal to sub-horizontal, lined burrows. Burrow diameter 4-10 mm, up to 21 cm in length. No branching; however, burrow crossovers and burrow collapse are common. Burrow fill structureless; sediment of wall lining varies from darker to similar in color to host rock.
Remarks: Specimens are assigned to *P. tubularis* on the basis of possessing a generally thinner lining compared to the burrow width.
Environmental distribution: *Palaeophycus tubularis* is found in the Lizard Creek Member, and was produced in a tidal-flat (Epstein and Epstein, 1972), as well as in the Shawnee Island Member, where it occurred under a shallow-water, sub-tidal marine environment.

Ichnogenus *Planolites* Nicholson, 1873
***Planolites beverleyensis* (Billings, 1862)**
Figure 2C

Description: Smooth, simple, horizontal to sub-horizontal, straight to slightly curved, unlined burrows. Burrow diameter 2-13 mm, maximum preserved length 11 cm. Burrow fill is lighter in color and coarser than surrounding rock.
Remarks: *Planolites* is differentiated from *Palaeophycus* largely on the basis of lacking a burrow lining (Keighley and Pickerill, 1995). *Planolites* occurs in marine (e.g., Moghadam and Paul, 2000), as well as nonmarine (e.g., Buatois and Mángano, 1993) environments. It has been interpreted to represent the active backfilling of a burrow formed by a mobile deposit-feeding animal (Pemberton and Frey, 1982).
Environmental distribution: *Planolites beverleyensis* occurs in the Lizard Creek Member, formed in a back-barrier lagoon; in the Wallpack Center Member, produced under shallow marine conditions subject to periodic, higher energy (likely storm) conditions; and in the Shawnee Island Member, formed under shallow-water, subtidal, marine conditions.

Ichnogenus *Protovirgularia* M'Coy, 1850
***Protovirgularia* isp.**
Figure 2D

Description: Unbranched, straight to slightly curved, series of v-shapes or chevrons forming a trail up to 85 mm in length, possessing a distinct to indistinct median furrow. Chevrons are wedge-shaped, curved, bilaterally symmetrical, up to 2 mm in width, 8-10 mm in length, forming a v-shaped angle ranging from 90°-145°.
Remarks: Potential tracemakers for *Protovirgularia* include crabs (Gümbel, 1879), arthropods or annelids (e.g., Greiner, 1972), and bivalves (e.g., Han and Pickerill, 1994).

Environmental distribution: *Protovirgularia* occurs in the Lizard Creek Member, produced in a lagoonal-tidal channel environment, and in the Wallpack Center Member, produced in a shallow marine environment, subject to periodic, higher energy conditions.

Ichnogenus *Rosselia* Dahmer, 1937
***Rosselia socialis* Dahmer, 1937**
Figure 2E

Description: Cylindrical burrows surrounded by a wall of concentric, funnel-shaped laminae, predominantly vertical or steeply inclined to the bedding. Laminae appear as nested cones, convex downward, and are infilled with alternating dark and light colored sediment. Cylindrical burrows, filled with sediment similar to the surrounding rock, occasionally extend through top of cone. Diameter of cylindrical burrows is 1-3 mm, while the upper funnel-shaped portion of the cone is 1-3.5 cm. Maximum recorded length, though incomplete, is 5 cm.
Remarks: Though *Monocraterion* and *Rosselia* are similar in having flared upper portions and a central burrow, the presence of a laminated fill throughout characterizes *Rosselia*. The tracemaker for *Rosselia* includes an annelid (Chamberlain, 1971), sea anemone (Książkiewicz, 1977), or a terebellid polychaete (Nara, 1995).
Environmental distribution: *Rosselia* is present in the Lizard Creek Member, and was formed under lagoonal-tidal channel conditions.

Ichnogenus *Skolithos* Halderman, 1840
***Skolithos linearis* Halderman, 1840**
Figure 2F

Description: Cylindrical to ellipsoidal, straight to slightly curved, unbranched, vertical to slightly inclined burrows. Diameter 2-7 mm, up to 40 cm in length. Burrow wall distinct, most exhibit thin lining of dark colored clayey material. Sediment filling the burrow is coarser, lighter in color, and similar in lithology to the enclosing rock, while in some, fill is weathered out. Occasionally, burrows show faint annulations.
Remarks: Characteristics such as uniformity of burrow diameter, burrow diameter, distinctiveness of burrow walls, ornamentation, and shape are used to differentiate ichnospecies of *Skolithos*. As such, the specimens are designated *S. linearis*, typified by the presence of straight, vertical burrows. *Skolithos* has been reported from marine (e.g., Ranger and Pemberton, 1988) to nonmarine (e.g., Fitzgerald and Barrett, 1986) deposits, and is mostly interpreted as a dwelling structure likely formed by polychaetes (e.g., Curran and Frey, 1977) or phoronids (e.g., Fenton and Fenton, 1934).
Environmental distribution: *Skolithos linearis* is found in the Shawnee Island Member, and formed in a shallow-water sub-tidal environment subject to periodic high-energy conditions, and in the Esopus Formation (Lower Devonian), produced in a deeper water marine environment.

Ichnogenus *Skolithos* Halderman, 1840
***Skolithos ?pusillus* Torell, 1870**
Figure 2G

Description: Cylindrical to ellipsoidal, straight, vertical, lined burrows. Diameter 3-4 mm, maximum length 9 cm. Burrows exhibit curved branches at their deepest end. Branches are inclined, slightly curved, lined, and up to 3 cm in length. Burrows are partly weathered out.

Remarks: The present burrows most closely resemble branching forms of *S. pusillus* (Frey and Howard, 1982), although their specimens have a much smaller burrow diameter. Nonetheless, Keighley and Pickerill (1997) indicated that one-dimensional size restraints (e.g., burrow diameter) do not provide adequate justification for separating ichnospecies. Thus, the specimens are tentatively assigned to *S. ?pusillus*.

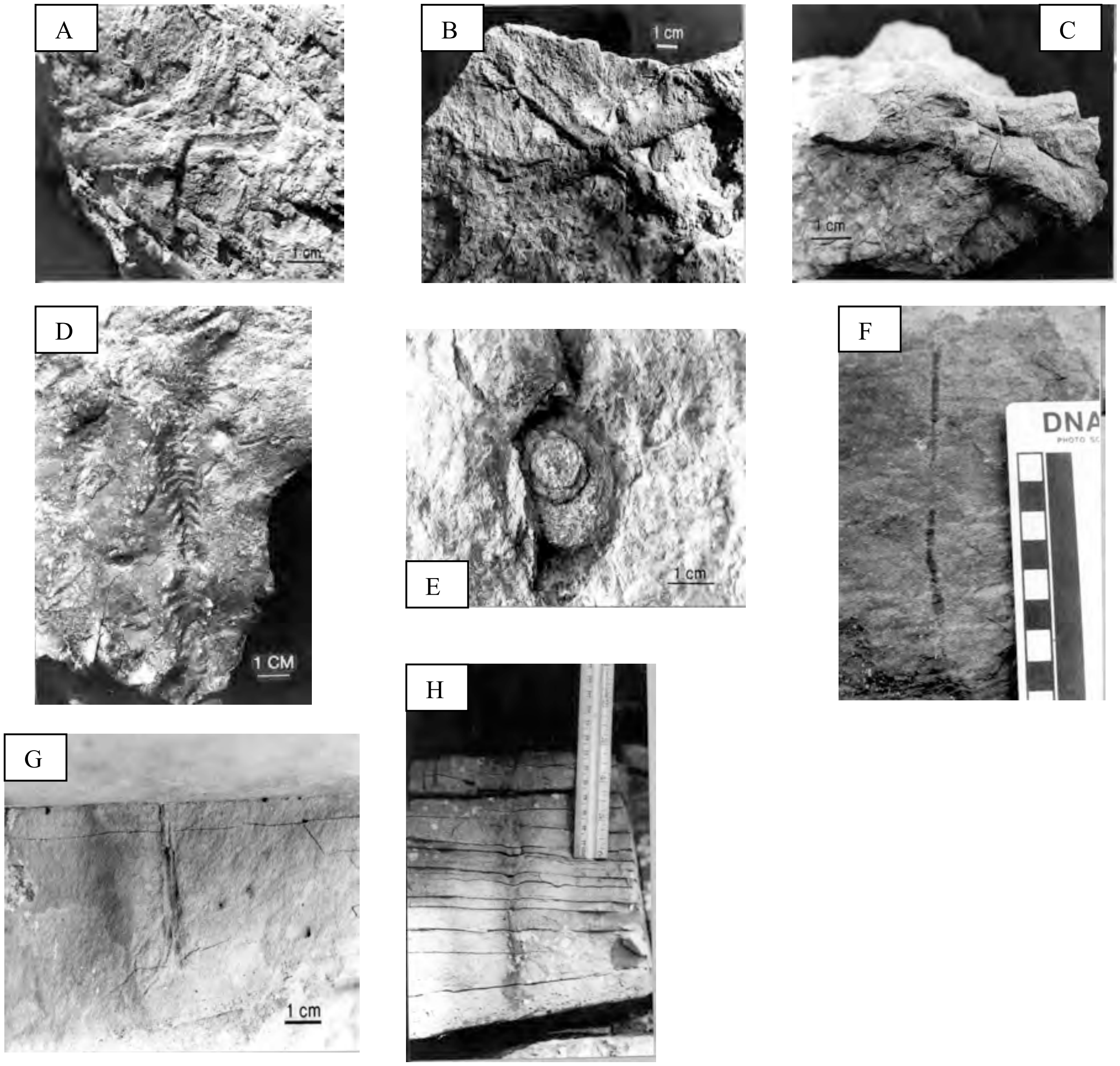

Figure 2. Trace fossils from the Delaware Water Gap National Recreation Area. (A) *Palaeophycus heberti* exhibiting partial collapse. (B) Specimens of *Palaeophycus tubularis*, one showing burrow lining. (C) *Planolites beverleyensis*. (D) *Protovirgularia* isp. preserved on upper bedding plane surface. (E) *Rosselia socialis* preserved on upper bedding plane surface. (F) Field photograph showing *Skolithos linearis* in vertical section. Scale in cm. (G) Field photograph of *Skolithos* ?*pusillus*. (H) Field photograph of *Skolithos verticalis*. After Metz, 1998a, 1998b, 2003a, 2003b**.**

Environmental distribution: Found in the Shawnee Island Member, *S. ?pusillus* was produced in a shallow water, subtidal environment, subject to periodic high-energy conditions.

Ichnogenus *Skolithos* Halderman, 1840
***Skolithos verticalis* (Hall, 1843)**
Figure 2H

Description: Straight to slightly curved, cylindrical to ellipsoidal, vertical to inclined, unbranched burrows. Diameter 1-5 mm, length 3-19 cm. Most specimens exhibit sharp, unlined walls filled with either darker or lighter sediment than the host rock, others show dark colored to iron stained, fine-grained, thinly lined, regular to irregular walls.
Remarks: A combination of shorter length as well as smaller burrow diameter differentiates *S. verticalis* from *S. linearis*. *Skolithos* is one of the most common trace fossils found in Precambrian to Holocene strata (Droser, 1991).
Environmental distribution: *Skolithos verticalis* occurs in the Lizard Creek Member, produced under shallow-water (e.g., tidal channel) origin; in the Wallpack Center Member, produced in a shallow marine environment during higher energy conditions; and in the Shawnee Island Member, formed in a shallow-water, sub-tidal environment subject to periodic high-energy conditions.

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THE DEVONIAN BIVALVE, *ARCHANODON CATSKILLENSIS*: A STATUS REPORT ON THE FIRST FRESHWATER MUSSEL FROM NEW JERSEY

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ABSTRACT

Archanodon catskillensis is a member of the oldest known genus of freshwater bivalves. Although the main occurrences of this species are in New York and Pennsylvania, its burrows are known from the Bellvale Sandstone (Givetian) of northern New Jersey. *A. catskillensis* has two shell morphs, each of which may be a separate species. *A. catskillensis* also differs from *A. westoni*, the other North American *Archanodon* species. *A. catskillensis* is the most common macroinvertebrate in non-marine facies of the Devonian Catskill clastic wedge, where it is found in channel fill and overbank deposits. *A. catskillensis* is an erect, semi-infaunal filter-feeder which often lived in clusters of many individuals. Its life habits thus appear very similar to those of many modern unionoid bivalves. Organic adventitious layers appear to be present in the shell microarchitecture of *A. catskillensis*. These points, together with its abundance and wide distribution in Catskill rocks, strongly implies that the genus should be included in the bivalve order Unionida. Disparities in shell form among *Archanodon* species indicate that taxonomic revision of the genus may eventually be necessary.

INTRODUCTION

Successfully colonizing new environments radically different from the old is a supremely difficult task for most lineages. The move into terrestrial environments by aquatic vertebrates is an obvious example. Judging from the large number of stenohaline marine clades (e.g., corals, cephalopods, brachiopods, echinoderms), movement by marine invertebrates into freshwater ecosystems was another difficult transition.

One group involved in the jump to life in fresh water is the bivalve order Unionida. In this paper we deal with the earliest part of unionoid phylogenetic history and the emergence of this group as a distinct freshwater bivalve clade. We do this by focusing on *Archanodon*, a Middle Devonian to Carboniferous molluscan genus generally considered to be the earliest known freshwater bivalve. Our particular interest here is *Archanodon catskillensis* (Vanuxem 1842), the only member of this genus recovered from the rocks of New Jersey. In this paper we review the paleobiology and taxonomic status of these animals, and propose additional avenues of research that will advance our understanding of them and of the bivalve move into fresh water.

Abbreviations for specimen repositories referred to in this paper are: AMNH - American Museum of Natural History, New York, NY; BCG - Brooklyn College Geology Department, Brooklyn, NY; NYSM - New York State Museum, Albany, NY; PRI - Paleontological Research Institution, Ithaca, NY.

ADAPTIVE BARRIERS

A prime adaptive impediment in transitioning from marine to freshwater environments is the need to accommodate biochemical systems to the new osmotic conditions of freshwater. For sedentary organisms water/salt balance issues are not the only class of severe adaptive hurdles involved in the passage from marine to freshwater ecosystems. Unidirectional current regimes typical of freshwater environments also present difficulties for clades of sedentary creatures. Bivalves are an excellent example. Post-larval juvenile and adult bivalves are sedentary or nearly so. The only truly mobile phase of bivalve ontogeny is the planktonic larval stage, and it is this upon which bivalves generally rely for geographic dispersal. The problem for bivalves is that the unidirectional current regimes of freshwater environments act to sweep planktonic larva downstream. As a result, bivalve capacity to colonize upstream habitats via larval dispersal is severely compromised. Only one bivalve order, the Unionida, can be said to have overcome this adaptive impediment. Unionoids surmounted this barrier in part by developing a larval stage in which larvae temporarily parasitize fish. Such parasitic larvae are referred to as glochidia. With their glochidial larvae, unionoids thus co-opt the motility of fish to resolve the hydrodynamic impediment inherent in the exploitation of freshwater environments.

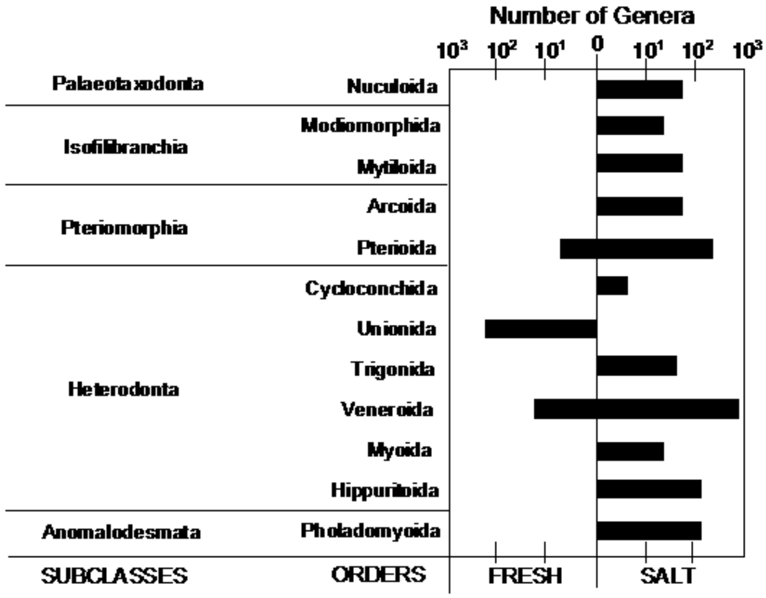

Figure 1. Preferences of bivalve genera for freshwater and marine habitats. Taxonomy from Pojeta (1987). Brackish water forms considered as marine. Data from Treatise on Invertebrate Paleontology, Part N, Mollusca 6, Volumes 1-3, and includes both modern and fossil genera. Redrawn from Chamberlain (2004, figure 1).

Measured in terms of generic richness, unionoids are by far the most diverse and successful freshwater bivalves (Figure 1). It is interesting to note, however, that numbered among the few non-unionoids found in freshwater are some that rely on the mobility of other objects to overcome unidirectional flow. The aggressive expansion of the zebra mussel (*Dreissena polymorpha*) into North American freshwater habitats in recent decades has been at least partly spurred by the ability of these sessile venerids to attach post-larvally to the exterior surfaces of mobile water craft.

ARCHANODON CATSKILLENSIS

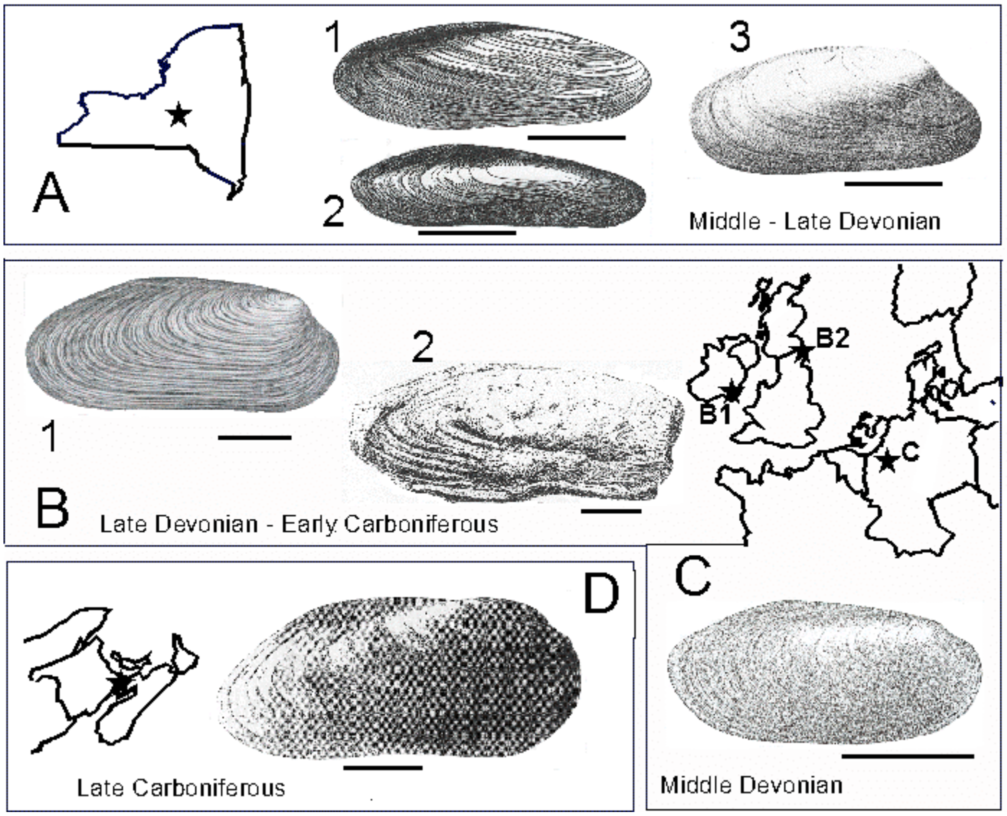

Figure 2. The four species of *Archanodon*. Illustrations are copies of the original figures in publications either defining each species or renaming it. Original species names as well as new names are given here. The modern name, *Archanodon*, was first used by Howse (1878), and was assigned to all four species by Weir (1969). The stars indicate the discovery sites of the four species. All scale bars = 5 cm. **A**: *Archanodon catskillensis*. 1, *Cypricardites catskillensis* (Vanuxem 1842, figure 1, page 186); 2, *Cypricardites angustata* (Vanuxem, 1842, figure 2, page 186); 3, *Amnigenia catskillensis* (Hall 1885, plate LXXX, figure 12). Hall combined Vanuxem's two species into the single new species, *Amnigenia catskillensis*. **B**: *Archanodon rhenana.* 1, *Amnigenia rhenana* (Beushausen 1890, upper figure on page 3). **C**: *Archanodon jukesii*. 1, *Anodonta jukesii* (Forbes, 1853; this figure is from Bailey 1861, figure 3a, page 16, which is the first published illustration of the species). 2, *Archanodon jukesii* (Howse 1873, plate XIV, figure a). Howse combined his Northumberland form and the Irish form of Forbes 1853, into the new genus, *Archanodon*. **D**: *Archanodon westoni.* 1, *Asthenodonta westoni* (Whiteaves 1893, plate 1, figure 1). Redrawn from Chamberlain (2004, figure 4).

Archanodon is an enigmatic bivalve genus of Middle Devonian to Late Carboniferous age. It is the earliest bivalve known from non-marine sedimentary rocks, and for this reason, *Archanodon* is generally viewed as the first freshwater bivalve. *Archanodon catskillensis* (Vanuxem, 1842) is one of four morphologically similar species of Devonian and Carboniferous freshwater bivalves placed in the genus *Archanodon* by Weir (1969). The other three species are *A. rhenana* (Beushausen, 1890), *A. jukesii* (Forbes, 1853), and *A. westoni* (Whiteaves, 1893). The occurrence of these species in time and space is indicated in Figure 2. *A. catskillensis* is the most widely studied and best known of the four species, and is also the only archanodont found in New Jersey rocks. It is the earliest freshwater bivalve to occur in what is now New Jersey.

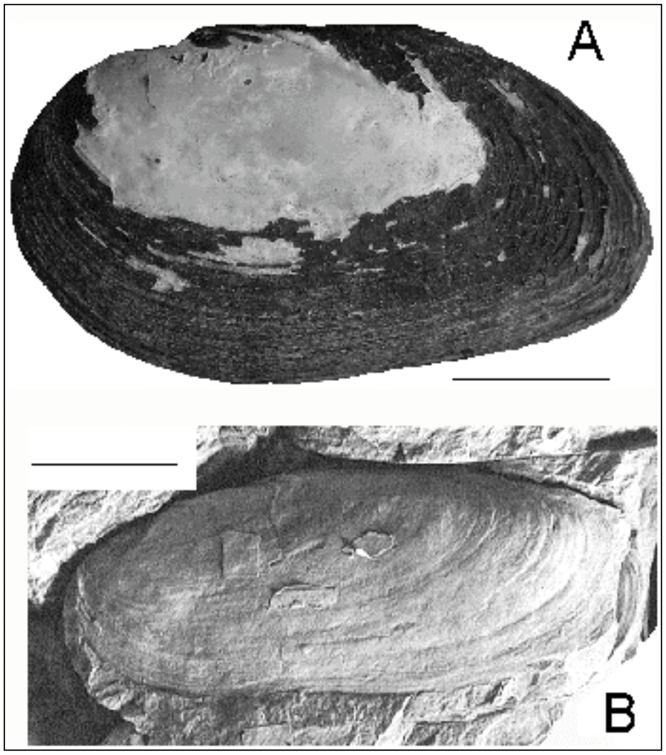

Figure 3. Shell morphology of modern and fossil freshwater bivalves. Shell anterior to the left; posterior to the right. All scale bars = 3 cm. A: Modern *Elliptio complanata*, Raritan River, Piscataway, New Jersey (BCG-133). B: *Archanodon catskillensis*, Oneonta Formation, Mount Upton, New York (AMNH-6331). This is one of the type specimens designated by Hall (1885) to define his *Amnigenia catskillensis*, which Weir (1969) renamed *Archanodon catskillensis*.

A. catskillensis has a smooth, subelliptical, inequilateral, equivalved shell similar in overall shape to the shells of many modern unionid bivalves, including the common eastern elliptio, *Elliptio complanata* (Figure 3). Notice in Figure 3 the enlarged posterior region of the shells, especially in *A. catskillensis*. *A. catskillensis* has prominent annular growth bands, but otherwise lacks shell ornamentation. This, too, is similar to *E. complanata* and many other modern freshwater bivalves. Estimates of growth rates in *A. catskillensis* based on measurements of annular band widths yield results similar to growth rate in modern *E. complanata*, i.e., in the range of 5 to 15 mm per year (Chamberlain, 2004). On the whole, *A.*

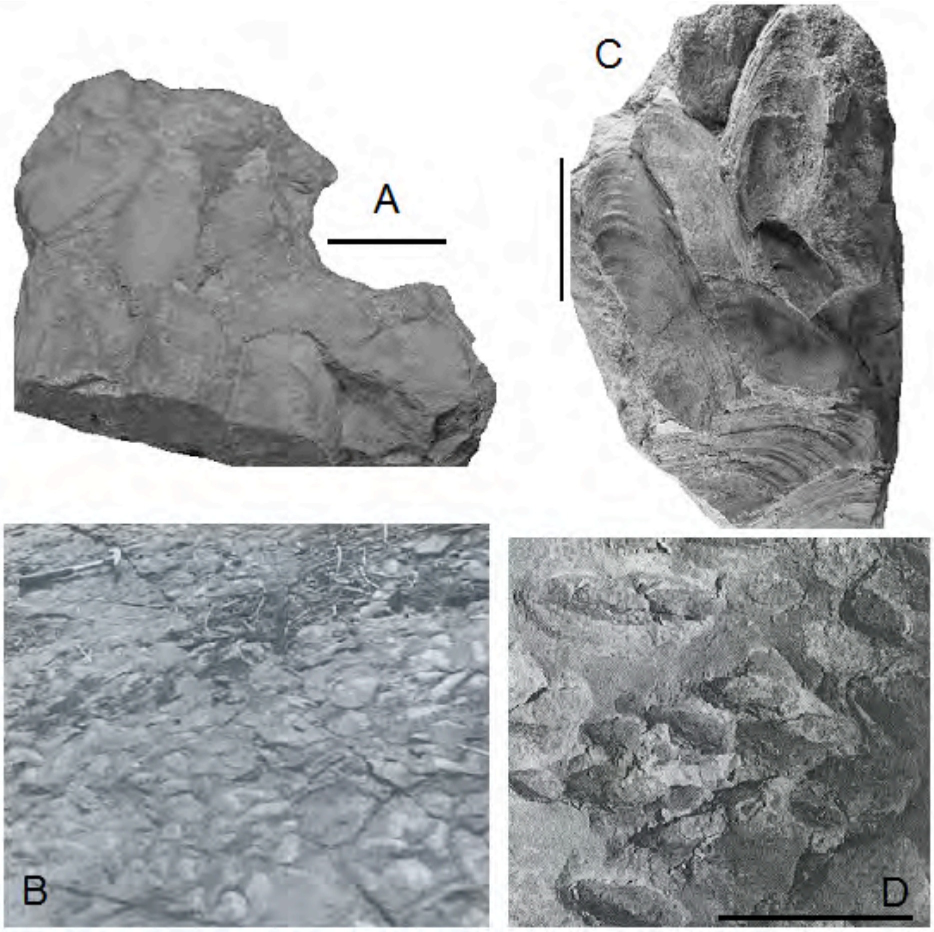

Figure 4. Preservation of *A. catskillensis*. All scale bars = 10 cm. A, B, and C show casts of transported, current oriented shells. D shows impressions of shells preserved in life position. A: Block showing ten partially imbricated, convex-up current oriented specimens (PRI-54631). Oneonta Formation, Downsville, NY. B: Bedding plane in the Towamensing Member of the Catskill Formation, Harrity, PA, showing hundreds of convex-up shell impressions. Also present but not visible in the photograph are a large number of vertical burrows made by *A. catskillensis*. Hammer is about 25 cm in length. From Thoms and Berg (1985), Figure 1A. C: Underside of block showing seven partially imbricated, convex-up current oriented specimens (BCG-EW1). Gilboa Formation, East Windham, NY. D: Bedding plane with cross-sections of casts of shells preserved in life position, some with current scour marks around the shell. Note that most specimens are aligned roughly parallel to flow direction. Oneonta Formation, Spring Quarry, Morris, NY. (From Bridge et al. (1986), Plate 3C.)

catskillensis specimens have maximum shell sizes about the same as the larger species of modern freshwater bivalves, such as *E. complanata* (Figure 3). However, a population of *A. catskillensis* at East Windham, NY, consists of shells that are considerably larger than those of other *A. catskillensis* populations (Friedman and Chamberlain, 1995), and of most modern freshwater bivalves as well. These authors also noted that these large specimens are found in beds with elevated organics and plant debris. Chamberlain (2004) and Chamberlain et al. (2004) suggested that size differences among *A. catskillensis* populations may be related to the availability of nutrients. Most occurrences of *A. catskillensis* are of shells preserved as transported accumulates with shells often imbricated and convex side up (Figure 4). However, in most cases, shell casts show essentially no abrasion, and many are still articulated, so that transport could not have been extensive. Animals preserved in life position (Figure 4) indicate that they adopt the more or less vertical, hinge down-commissure up, orientation with the shell posterior facing upstream that is typical of most modern freshwater bivalves. They also appear to have lived in groupings of many closely spaced animals. This is quite similar to the patchy microscale distribution of individuals seen in modern freshwater bivalves in which individuals are often concentrated into discrete clusters by the patchiness of sediment distribution, substrate stability, or other environmental factors within river channels (e.g., Donnelly, 1993; Kat,1982; Vannote and Minshall, 1982; Bauer, 1988; Strayer, 1993; Di Mayo and Corkum, 1995).

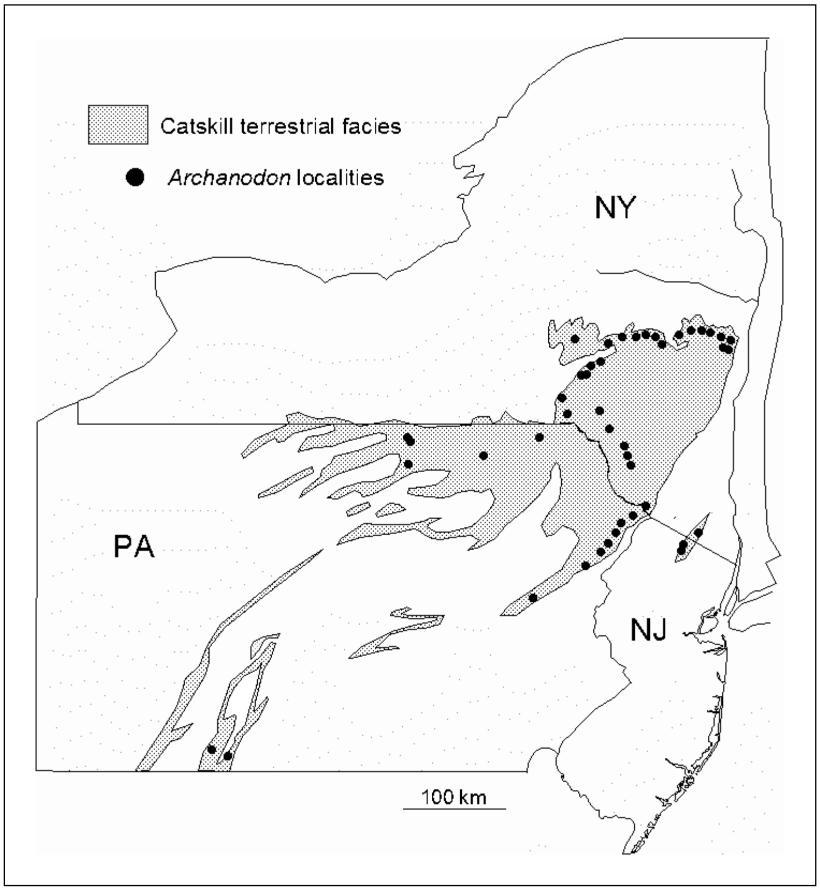

Figure 5. Collection localities for *A. catskillensis* based on personal discovery, on citations in the *Archanodon* literature, and information taken from museum specimen labels. The data are for sites preserving shell casts, burrows, and both burrows and shell casts as described in the text. In general, the oldest exposures (Middle Givetian) are in the east, in New Jersey and the Catskill Front. Exposure age decreases westward into the Famennian. Some symbols represent two or more closely spaced sites.

As noted in Figure 5, *A. catskillensis* occurs in two localities in New Jersey. Both of these occurrences are in the Bellvale Sandstone (Givetian) of the Green Pond Outlier in northwestern Passaic County on land that is now part of the City of Newark watershed system. Interestingly, these sites, described originally by Berg (1977), contain only burrows (Figure 6A). Body fossils do not occur. However, the burrows are distinctive and satisfy all eight criteria erected by Chamberlain et al. (2003) and Chamberlain and Chamberlain (2005) for distinguishing *Archanodon* burrows from burrows made by other animals. Berg (1977) also considered the burrows to be those of *Archanodon*. From Rickard (1975) and Ver Straeten et al. (1995), the age of the Bellvale sandstone is most likely Middle Givetian. This makes the New Jersey burrows the oldest known occurrence of *A. catskillensis* in as much as they lie below the oldest known body fossils of this species which are found in the Gilboa Formation of the Catskill Front in New York (Friedman & Chamberlain, 1995).

Burrows made by *A. catskillensis* are impressive structures, sometimes up to a meter in length (Figure 6). They are often interpreted as escape burrows, because they lack the upward expansion in diameter Reineck (1958) and Bromley (1996) associate with many bivalve domicile burrows. This view may be correct in some instances, but escaping a meter of anastrophic sediment deposition seems beyond the capacity of bivalves lacking mantle fusion (Stanley, 1970; Kranz, 1974). Most long, vertical *A. catskillensis* burrows, such as those illustrated in Figure 6, closely parallel the features of modern marine bivalve burrows made in environments dominated by slow, relatively continuous deposition (e.g., Bromley, 1996, fig. 4.8). Although some workers have discussed burrowing in modern freshwater bivalves (e.g., Trueman, 1968; Amyot and Downing, 1997; Lawfield and Pickerill, 2006), burrowing capacity of modern freshwater forms remains poorly understood, so that little interpretive benefit derives from the living fauna in this regard. A concerted effort to improve the picture here would be well worthwhile.

IS *A. CATSKILLENSIS* A UNIONOID?

In its elongate, inequilateral shape and enlarged posterior region, the shell of *Archanodon* resembles the shell form typical of modern unionoids. These parallels, together with its freshwater habitat, have led to the view that *Archanodon* is the earliest known member of the bivalve order, Unionida.

Identification of *Archanodon* as a unionoid dates to the discovery of the first specimens of *Archanodon catskillensis*, one of the species currently included in the genus, in central New York by Vanuxem (1842) who recognized their association with fluvial sediments and their general morphological resemblance to modern unionoids, particularly to the genera *Unio* and *Anodonta*. However, the poor preservation of *Archanodon* specimens collected so far has precluded detailed comparison to modern unionoid shell form, particularly with regard to the hinge and shell musculature. Hinge morphology is a crucial character in bivalve taxonomy, but is totally unknown in *Archanodon*. Coupled with this is the fact that there is no current means based on shell morphology to recognize in fossil specimens such important aspects of unionoid soft anatomy as a glochidial larval phase and the modification of the gills to form a marsupium (larval brood chamber). In the most recent review of the genus to date Weir (1969) interpreted the scattered and spotty distribution of *Archanodon* fossils as indicating that these animals probably did not possess glochidial larva, and therefore did not support the view that they were true unionoids. The result of these uncertainties was that Weir (1969) suggested that the unionoid status of *Archanodon* should be considered provisional only.

More recently, Chamberlain et al. (2004) and Chamberlain (2004) described some well-formed shell casts of *A. catskillensis* from a site in Greene County, NY, which show a mode of shell

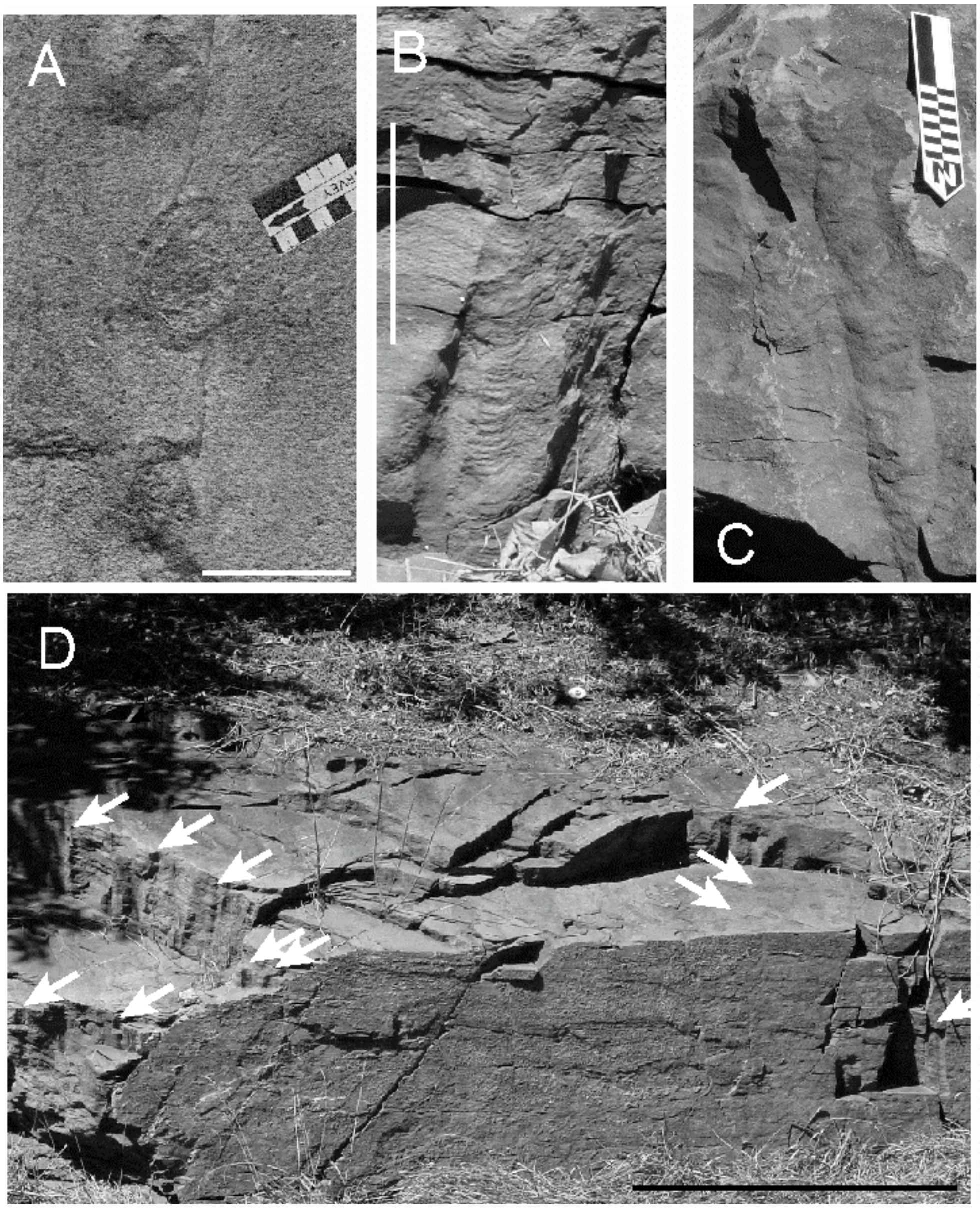

Figure 6. *A. catskillensis* burrows. **A**: Three burrow cross-sections exposed on bedding plane. Scale bar = 5 cm. Bellvale Sandstone, West Milford, NJ. From Berg (1977), Figure 4. **B**: Burrow in longitudinal view. The concave-up menisci within the burrow and down-turned bedding planes adjacent to it are features typical of well preserved *A. catskillensis* burrows. Scale bar = 25 cm. Towamensing Member, Catskill Formation, Harrity, PA. From Chamberlain (2004), Figure 12B. **C**: Two parallel burrows. Large divisions in scale at upper right = 10 cm. Oneonta Formation, Jewett Quarry, Jewett, NY. From Chamberlain et al. (2003). **D**: Burrowed sandstone of the Towamensing Member, Catskill Formation, Harrity, PA. Scale bar = 2 m. Left facing arrows indicate burrows seen in longitudinal view. Right facing arrows indicate a cluster of burrows seen in cross-section on bedding plane surface. From Chamberlain et al. (2003).

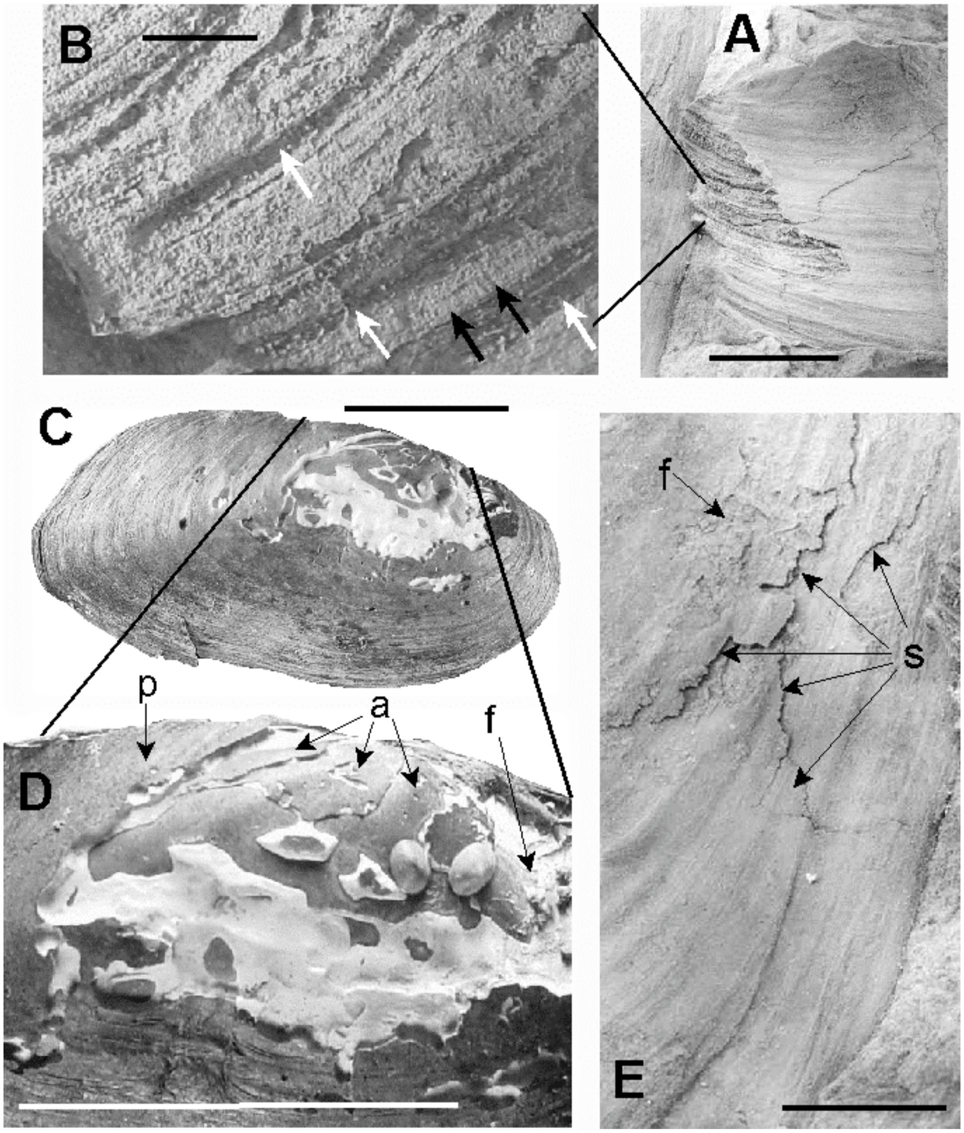

Figure 7. Shell cast impressions of shell microstructure of *A. catskillensis* compared to shell structure in modern *Elliptio complanata*. All scale bars = 2 cm, except B. Scale bar in B = 2 mm. Redrawn from Chamberlain (2004), Figures 14 and 15. A: *A. catskillensis* specimen (BCG-EW1a), Oneonta Formation, East Windham, NY, showing impressions of internal structure of shell. B: Enlargement of a portion of A. Black arrows point to what appear to be impressions of stacks of tabular crystals of nacreous layer. White arrows point to dark, organic rich layers that may be the remnants of organic adventitious sheets within shell. C, D, E: Shell dissolution structures in *Elliptio* and *Archanodon*. C: Modern *Elliptio complanata* (BCG-DF11) from the Delaware River at Dingmans Ferry, PA, showing etched surface resulting from dissolution of shell carbonate by Delaware River water. D. Enlargement of C, showing details of dissolution surface. p - periostracum; a - organic adventitious sheet; f - flaky, erose surface. E: *A. catskillensis* (BCG-EW1b), East Windham, NY. s - irregular, stepped surface suggestive of horizontal organic adventitious sheets; f - flaky, erose surface.

microstructure and, particularly of shell flaking and breakage, which is closely analogous to that seen in modern unionoids (Figure 7). We argued from this that the shell of *Archanodon* may well have contained the prominent adventitious organic sheets that are a uniquely unionoid character.

Much has been learned of the actual distribution and abundance of *A. catskillensis* in the years since Weir's (1969) review of the genus. A summary of our current sense is shown in Figure 5. It is evident from Figure 5 that *A. catskillensis* is well-distributed within terrestrial facies of the Catskill Clastic Wedge. It is particularly common in point bar, levee, and overbank deposits. At most localities preserving shell casts, *A. catskillensis* can be said to be common in that hundreds of casts often occur. In the Catskill Mountains of New York and the Delaware Valley of northeastern Pennsylvania, *A. catskillensis* is the most abundant and widespread benthic macroinvertebrate to be found in non-marine Catskill Delta rocks (Friedman & Chamberlain, 1995; Chamberlain, et al., 2004). To the west and southwest, *A. catskillensis* occurrences are fewer, but this undoubtedly reflects the fact that little effort has been spent searching for them in this region. It is important to note that the spatial distribution of many modern unionoids is strongly discontinuous, even within a single drainage system (e.g. Smith, 1982; Strayer, 1987; Strayer and Jirka, 1997).

These considerations suggest to us that the distribution of *A. catskillensis* is not significantly different from what is seen today among modern unionoids, especially when viewed through the filter of 350 million years of geologic time and the vagaries of preservation and erosion that go with it. The idea that geographic distribution weighs against glochidial larva in *A. catskillensis* (and thus *Archanodon* generally) therefore appears to us ill-founded. We suggest that although one cannot yet be certain, the weight of biogeographic evidence points in favor of *Archanodon* being a true unionoid.

TAXONOMIC STATUS OF *A. CATSKILLENSIS*

In addition to the question of whether *A. catskillensis* is actually a unionoid, there is a second systematic issue we want to address here, and that is whether *A. catskillensis* is actually a single species. We should state at the outset that the unionoid fossil record and unionoid shell morphology do not conduce to straightforward interpretation of this question. The main problems are twofold: 1) the incompleteness of the unionoid fossil record; and 2) the high degree of morphologic variability in many unionoid taxa. Unionoid generic diversity considered as a function of geologic time (Figure 8) has two attributes that mitigate against firm conclusions at this time. First, diversity tracks rock availability (Figure 8, inset). Not only are real diversity fluctuations, i.e. those not related to sample abundance, difficult to recognize in such a situation, but more importantly, one can not feel confident that the known record reports actual diversity. Second, it is clear that the unionoid fossil record suffers from what Raup (1976) called "the Pull of the Recent", i.e. that it is heavily weighted toward modern taxa. This, too, implies that the unionoid fossil record may not be completely representative of actual unionoid diversity and perhaps therefore not explicitly helpful in questions about *Archanodon* systematics. The morphological difficulties are, first, that many of the criteria used to define unionoid clades are features of the soft tissue not yet recognizable in fossils, and second, unionoid shell morphology is notoriously plastic judging from modern examples. Thus, the systematics of fossil unionoids is subject to considerable uncertainty, especially the further back in time one goes. It is not surprising, when confronted by such problems, that Weir (1969) recommended exercising caution in such matters and only provisionally assigned all *Archanodon*-like forms to a single taxon of uncertain status relative to other unionoid taxa . While we recognize the cogency of Weir's (1969) view, new insights into the paleobiology of *A. catskillensis* outlined above make returning to such issues of some value because this new evidence suggests that it may be necessary to eventually revise the status of *A. catskillensis*.

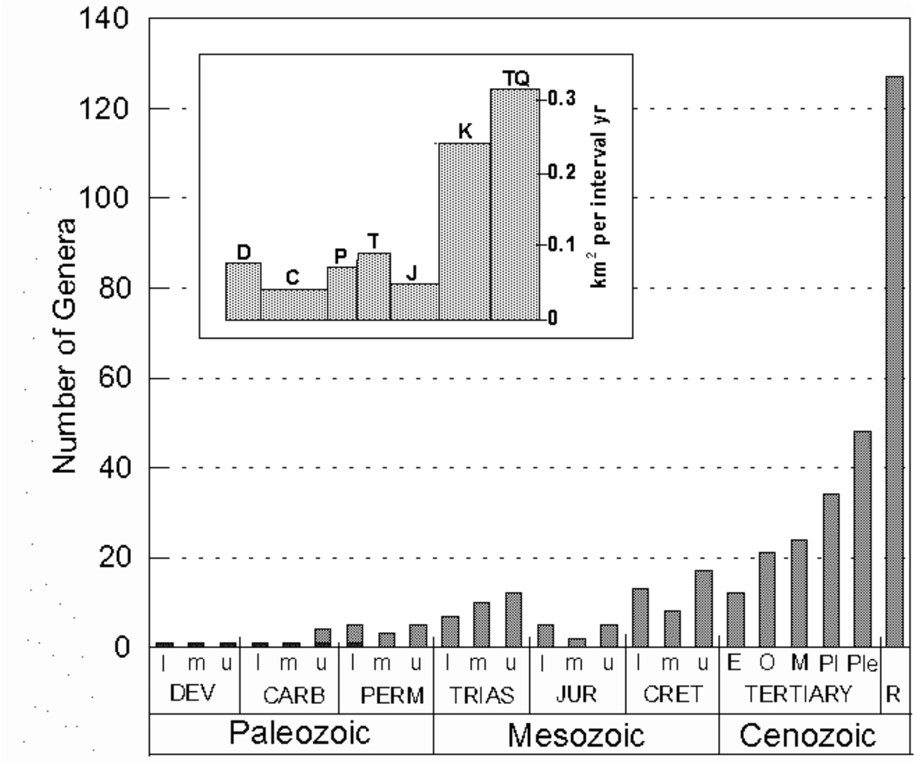

Figure 8. Generic diversity of unionoids through time. Data from Treatise on Invertebrate Paleontology, Part N, Mollusca 6, Volume 1, pgs 401-471. Black bars - number of archanodont genera. Gray bars - number of other (i.e., non-archanodont) unionoid genera. Redrawn from Chamberlain (2004, figure 3). Inset: Global exposure area of sedimentary rocks tabulated by period. Redrawn from Raup (1976, figure 2). The similarity of the diversity curve to Raup's exposure area curve is apparent. We note that Raup's data are for all sedimentary rocks, but since it is a global dataset, we assert that the inset also applies to non-marine sediments also.

Among specimens of *A. catskillensis* are a small number that differ markedly in shell shape from the species norm. Figure 9 shows two specimens originally collected by Vanuxem and which were part of the specimen base he used in his 1842 paper to define what is now *A. catskillensis*. Figure 9A shows a specimen having the subelliptical shape typical of *A. catskillensis*. Figure 9B shows what Chamberlain (2004) and Chamberlain and Chamberlain (2005) called a "narrow" shell morph. Not only is the shell compressed along its length, giving it a very narrow profile, but the valves are also more acutely arched, giving it almost a cylindrical shape along the long axis of the shell, rather like that seen in modern jack-knife clams (e.g., *Ensis*). Chamberlain (2004) also pointed out that the narrow morph also has a prominent posterior gape (Figure 9C), a feature not mentioned by Vanuxem (1842), but more importantly a feature which has never been observed in the normal morph.

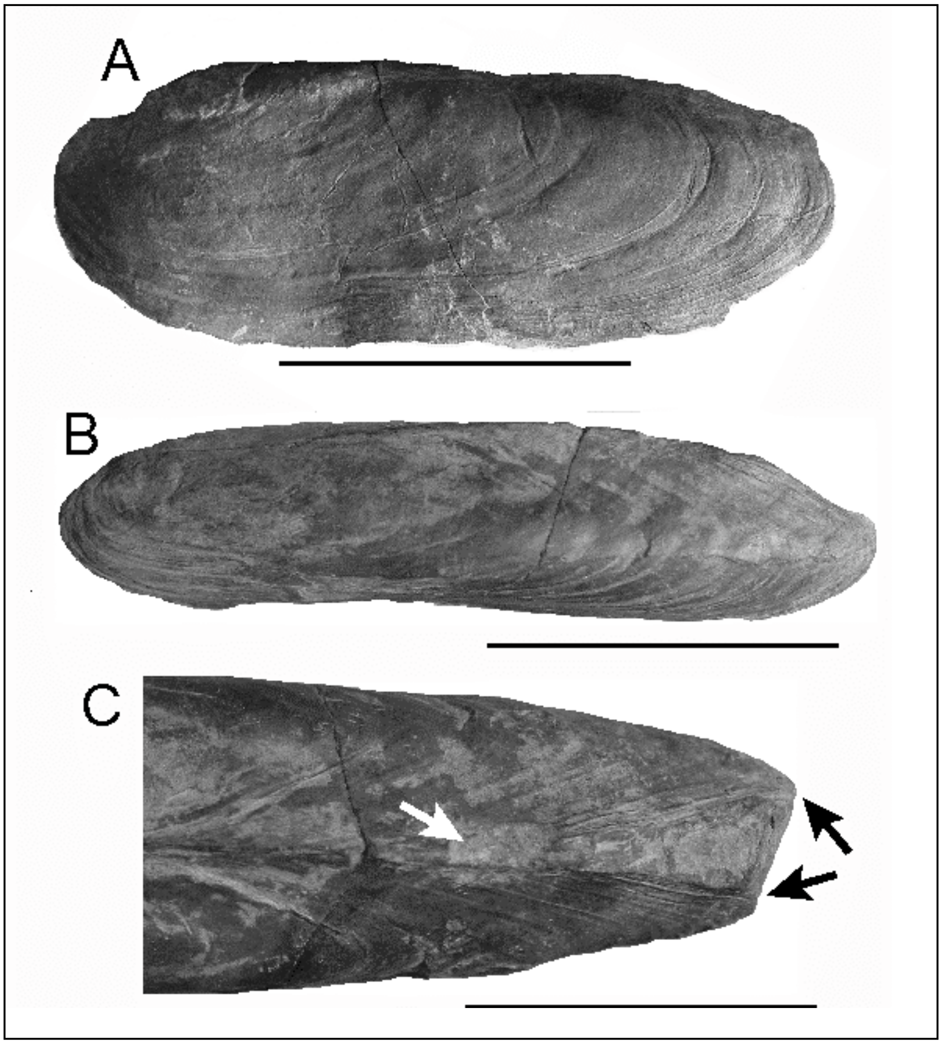

Figure 9. Intraspecific variation in shell form in *A. catskillensis*. Specimens illustrated here were originally collected by Vanuxem (1842. **A**: Normal morph (NYSM-E426a). Shell anterior to the left; posterior to the right. Scale bar = 5 cm. **B**: Narrow morph (NYSM-E426b). Same orientation as in **A**. Scale bar = 5 cm. **C**: Close-up of the narrow morph (NYSM-E426b) photographed along hinge line; shell posterior to the right. Scale bar = 4 cm. White arrow indicates piece of missing shell at the hinge. Black arrows point to gaped posterior commissure.

Among modern unionoids such shell disparities as observed between the normal and narrow morph, if widespread among individuals, are usually considered sufficient to separate taxa, and indeed, Vanuxem (1842) recognized the narrow morph as a species (*Cypricardites angustata*) distinct from the normal form which he named *Cypricardites catskillensis*. Hall (1885) argued that Vanuxem's *C. angustata* was secondarily distorted and united Vanuxem's two species into a single species, *Amnigenia catskillensis*, which eventually (Weir, 1969) became *Archanodon catskillensis*. However, Hall was incorrect, Vanuxem's specimen of *C. angustata* is not deformed in any way. It is simply different than *C.*

catskillensis.

Asserting the validity of the narrow morph as a species distinct from *A. catskillensis*, however, is not justified at this time in our opinion. We see two main reasons for this stance. First, the systematic significance of the elongated shell shape is not beyond question. Were the narrow and normal morphs actually different species, one would expect relatively few or no morphological intermediaries between the two end members, and secondly, one would expect to see some degree of ecological exclusion between the two morphs. Based on the *A. catskillensis* fossil record, as it is currently known, these expectations may not hold. Figure 10 shows a small slab of rock studied by Clarke (1901). It contains several specimens that are more elongated than normal, but not to the extent of Vanuxem's specimen (Figure 9B), and which are preserved together with normal morphs in what appears to be a life assemblage. This situation is not consistent with the morphological and ecologic exclusion typical of closely related species. It is more in line with simple intraspecific variability.

Figure 10. Sandstone slab (NYSM-5020) from the Oneonta Formation illustrated in Clarke (1901) showing a probable life assemblage of *A. catskillensis.* Scale bar = 10 cm. The slab shows casts of elongated individuals mixed in with shell casts of normal aspect. Left facing arrows indicated elongated individuals. Right facing arrows normal morphs. Asterisks indicate shells in which the valves are preserved partly open or with missing shell material. None of these specimens have gaped commissures.

The second point is that among modern unionoids gaped individuals are sometimes found together with normal, ungaped members of a population. Trueman (1968) reports just such an occurrence with *Margaritifera margaritifera*, and notes that gaping is correlated with the development a pronounced ventral sinus. However, the gape is anterior rather than posterior as in *A. catskillensis*. Coker et al. (1921) reported that gaped specimens frequently occur in many of the western North American species they studied. However, they showed that at least in some of these species the cause was parasite infestation of the gaped individuals. Pathologic conditions clearly have no taxonomic import, and to the extent that this may be the cause underlying Vanuxem's gaped material, it does not weigh strongly in favor of revising the species.

In both overall shell shape, and the occurrence of a gape, current data are taxonomically equivocal. One can not feel confident in invoking these observations to suggest splitting *A. catskillensis* into a normal and a narrow species, but at the same time it is not impossible think that as more precise data are generated, this may eventually become necessary. What is needed to resolve this dilemma is a focused study of shell form and the geographic and lithologic distribution of the two shell morphs.

Before leaving this question altogether we would point out that the Nova Scotian species of *Archanodon*, *A. westoni*, also has a gape - an anterior one (Chamberlain, 2004), which is present in all specimens we have examined to date that are sufficiently complete to show it. This seemingly points to important systematic consequences, at least for *A. westoni*, but there are very few specimens of this species extant. Our observation is based on only three individuals. Analysis of more specimens, when they become available, is needed to confidently unravel this issue.

QUO VADIS *ARCHANODON?*

While much has been done in recent years, it is clear that much work remains in order to solidify some of the points discussed here. Work on both fossil and modern forms would be advantageous. With regard to modern unionoids, their value as paradigms for interpreting *Archanodon* taxonomy and paleobiology would greatly benefit from two specific lines of investigation: 1) determining whether there is a link between the possession of glochidial larvae and shell form that can be exploited in interpreting fossil unionoids; and 2) quantifying the burrowing capacity and burrowing strategies of modern unionoids, as well as the relation between shell form and burrowing.

Turning to fossils, continued field work is needed to improve the specimen base needed for analytical work on *Archanodon* paleobiology and paleoecology, and to hopefully find the *Archanodon* holy grail - specimens with intact pristine shell carbonate. Success in these endeavors would go a long way toward answering the questions raised here about the status of the genus and its species; about details of ontogeny and growth; about phylogenetic relationships; burrowing and its function; in short, about practically every aspect of these fossils in which paleontologists might conceivably have an interest. Only the surface has been breached, the treasure remains below. And this chest needs to be opened in order to reflect on the larger goal of understanding the root causes of the bivalve move into freshwater environments. To our minds, perhaps the most perplexing and interesting aspect of this transition is why *Archanodon* is the sole freshwater bivalve known from the Middle Devonian to the Late Carboniferous (at which point the Anthracosiacea, the other Paleozoic freshwater bivalve superfamily, finally appears). This is not the explosive exploitation of new life styles and ecosystems seen in the vertebrate colonization of the land. What was holding bivalves back?

ACKNOWLEDGMENTS

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ESTIMATING SPEEDS OF DINOSAURS FROM TRACKWAYS: A RE-EVALUATION OF ASSUMPTIONS

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ABSTRACT

For 30 years, using equations determined by Alexander (1976), paleontologists have estimated speeds of dinosaurs from their trackways; the fundamental assumption, based on limited observations, was that dinosaur hip height is approximately four times foot length. Thulborn (1990) subsequently determined that the leg length to foot length ratio ranges from 4.5-6.0, according to type and size of dinosaur. Given that the focus of many published footprint studies is to estimate dinosaur speed from Alexander's equations, it is critical that the hip height of the track maker can be ascertained from the footprint measurement. If there is high variability in the ratio of hip height:foot length within a group of dinosaurs, speed estimates are going to be extremely unreliable.

This study examined the relationship between foot length and leg length in a variety of dinosaurs. Measurements of 24 dinosaur specimens included ornithischians (bipedal and quadrupedal), theropods, dinosauriforms, birds, and sauropods. Leg length was defined as femur + tibia + metatarsal III; foot length was defined as that part of the foot preserved in footprints (digit III phalanges ± claw + metatarsal III – metatarsal IV). Leg and foot lengths were compared and it was found that in bipedal ornithischians the foot to leg length ratio is ~5.4-5.9, and in theropods, 2.8-4.2. Contrary to previous studies, we found that (1) there is no correlation between dinosaur size and foot to leg length ratio, (2) the foot to leg length ratio is greater than previously estimated, and (3) the foot to leg length ratio is highly variable for each group of dinosaurs. We conclude that estimating dinosaur speed from trackways should not be undertaken lightly, and the results be interpreted with caution.

INTRODUCTION

In 1976, Alexander proposed that dinosaur speeds could be estimated from their trackways, using an equation based upon the principals of fluid dynamics:

$$u \approx 0.25 g^{0.5} \lambda^{1.67} h^{-1.17}$$

where λ is stride length (length between successive prints of same foot), h is hip height, g is acceleration due to gravity, and u is velocity. While λ can be measured directly from a trackway, h must be estimated. Using published data and estimated measurements from photographs, Alexander (1976) determined that for many bipedal dinosaurs including both theropods and ornithopods, the footprint length (FL) would be $0.23h$ to $0.28h$, assuming that the rear of the footprint was the metatarsophalangeal articulation. For the sauropod *Apatosaurus*, Alexander (1976) estimated that footprint length was $0.25h$. Alexander (1976) therefore stated, for simplicity, that hip height h was four times the footprint length (which was assumed to always be only the digital portion of the foot). Within a short time, several studies appeared which provided dinosaurian speed estimates from trackways (e.g., Russell and Béland 1976, Tucker and Burchette 1977, Coombs 1978, Thulborn and Wade 1979, Farlow 1981, Thulborn 1981).

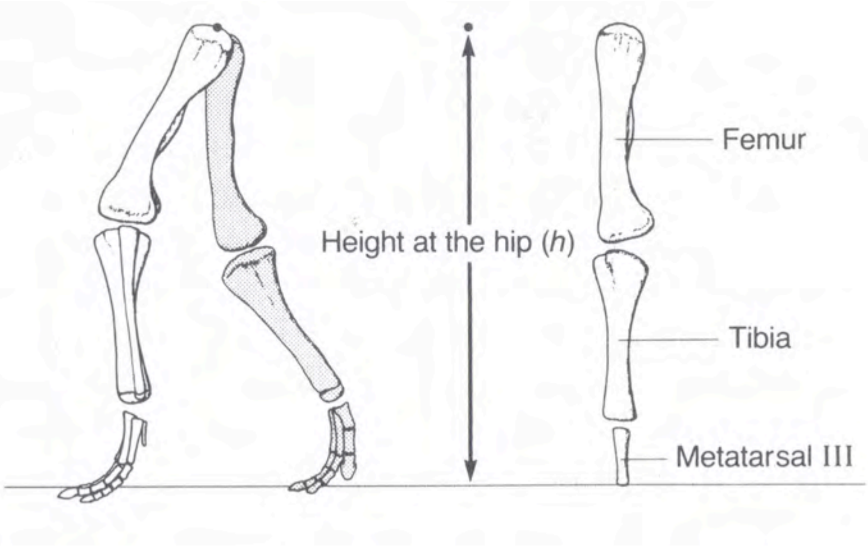

Figure 1. Hip height above the ground depends on the angle of flexion at the knee, ankle, and metatarsophalangeal joints (left), which must be estimated; Thulborn (1990) eliminated this uncertainty by approximating hip height to be the sum of the femur, tibia and mt III lengths (right). (Image modified from Thulborn 1990.)

Group	Morphometric	Allometric
Small theropods	$h \approx 4.5FL$	$h \approx 3.06FL^{1.14}$
Large theropods	$h \approx 4.9FL$	$h \approx 8.6FL^{0.85}$
Small ornithopods	$h \approx 4.8FL$	$h \approx 3.97FL^{1.08}$
Large ornithopods	$h \approx 5.9FL$	$h \approx 5.06FL^{1.07}$
Small bipedal dinosaurs (in general)	$h \approx 4.6FL$	
Large bipedal dinosaurs (in general)	$h \approx 5.7FL$	
Theropods (in general)		$h \approx 3.14FL^{1.14}$
Ornithopods (in general)		$h \approx 3.76FL^{1.16}$

Table 1. Equations for hip height for various dinosaurian groups as determined by Thulborn (1989, 1990). Morphometric equations assume constant ratios between the various hind leg bones; allometric ratios consider that dinosaurs of different sizes will not have the same hip height:foot length ratio. For the morphometric equations, *FL* is the footprint length (i.e., length of digit III); for the allometric equations, *FL* was substituted for metatarsal III length. ‘Small’ dinosaurs are defined as those with footprint lengths < 25 cm; conversely, ‘large’ dinosaurs are those with footprint lengths > 25 cm.

Thulborn (1990) discussed the possible meanings of 'hip height' (height of the hip above the ground [Alexander 1976], height of the hip joint above the ground in a dinosaur skeleton [Thulborn and Wade 1984], height of the hindlimb from top of the femur to sole of the foot [Thulborn 1982]), and stated that, except in very large dinosaurs, a practical measure of hip height could be considered the sum of the lengths of the femur, tibia, and third metatarsal (Figure 1). Thulborn (1990) provided revised estimates of the foot length to hip height ratio, recognizing that different groups of dinosaurs had slightly different ratios (Table 1). In addition, Thulborn (1990) noted that this ratio would also vary over an individual dinosaur's life due to allometric growth patterns; thus, this ratio would overestimate hip height for juveniles and underestimate it for adults. Because it is not possible to identify the trackmaker *species* for any given footprint – at best, we might identify the trackmaker to family level (see Rainforth 2005 for discussion) – we are unable, for a given footprint, to ascertain whether it is a juvenile or small individual of a large species, or a full-grown adult of a smaller species.

Thulborn (1990) also noted that the length of metatarsal III correlates to the sum of the lengths of the femur, tibia, and metatarsal III (i.e., the approximate hip height). He provided a series of allometric equations for bipedal dinosaurs (Table 1), with the assumption that metatarsal III is approximately equal in length to the phalangeal portion of digit III, which (in turn) is assumed to be footprint length.

Recently, Henderson (2003) constructed computer models to test the hip height prediction equations of Alexander (1976) and Thulborn (both morphometric and allometric equations [summarized in Thulborn 1990]) for three theropods (*Tyrannosaurus rex, Allosaurus fragilis*, and *Coelophysis bauri*) and three ornithopods (*Edmontosaurus regalis, Iguanodon bernissartensis*, and *Hypsilophodon foxii*). Henderson (2003) recognized that hip height would vary during the step cycle, and with different limb flexion angles. The models generated simulated trackways, from which footprint length could be measured and methods for determining hip height from footprint length could be tested. Henderson (2003) concluded that for all of these dinosaurs except *Coelophysis* (the only 'small theropod' *sensu* Thulborn 1990), Alexander's method for estimating hip height (i.e., $h = 4$ FL) provided the most reliable results (for *Coelophysis*, Henderson concluded that Thulborn's morphometric equations provided the best estimates of hip height).

THIS STUDY

Alexander's (1976) equation for estimating dinosaur speeds from trackways has received much use since it was first introduced, and (as shown above) many refinements have been suggested. However, there seem to be some fundamental assumptions that have not been examined in a manner that considers both the skeletal structure and footprint morphology. Some questions that should be addressed include:

1. Does it make a difference whether we use actual hip *height* in Alexander's (1976) speed equation, or will summing the lengths of the femur, tibia and metatarsal III provide an adequate proxy for hip height? (The height of the hip depends on the angle of flexion in the knee, ankle, and metatarsophalangeal joints, as well as the amount of flesh separating the foot from the ground; these must all be estimated. In contrast, the lengths of the femur, tibia, and metatarsal III can be measured directly from skeletons.)
2. *FL*, footprint length, is measured directly from the footprint. However, what bones does this length correspond to? It is not simply the length of the digit III phalanges (including ungual), because mt III is the longest metatarsal; the proximal pad in footprints of bipedal dinosaurs is formed by the metatarsophalangeal pad on digit *IV*. All equations to date use either morphometric ratios (e.g. Thulborn 1990) or allometric ratios with the assumption that metatarsal III is the same length as the phalangeal portion of digit III, which in turn is

the footprint length. What, then, is the relationship between the measured footprint length and the length of mt III?

3. In light of Henderson's (2003) models, is there a simple relationship between hip height and foot length (e.g., $h = 4FL$)? Do we need to resort to allometric equations for any groups of bipedal dinosaurs?

It appears, from casual observation of either mounted dinosaur skeletons or illustrations of dinosaurs, that the $h{:}FL$ ratio is highly variable, both within and between dinosaurian groups. If this is in fact the case, then assuming $h = 4FL$ (Alexander 1976, Henderson 2003) is going to result in highly inaccurate estimates of dinosaurian speeds from trackway data.

MATERIALS

Feet and legs were measured in 44 specimens, including dinosauriforms, bipedal and quadrupedal ornithischians, sauropods, theropods, and birds. However, due to incomplete material, only 24 of these specimens are used in the present analysis. All specimens used in this study consisted of bones from a single individual; while composite and/or reconstructed dinosaurs abound in museum displays, they were excluded here.

Several Late Triassic and Early Jurassic dinosaur specimens are included in the present study, including *Coelophysis* (YPM 5705), *Dilophosaurus* (UCMP 37302), and *Scelidosaurus* (BMNH R1111) – small theropod, large theropod, and quadrupedal ornithischian respectively.

(Institutional abbreviations: BMNH, Natural History Museum (London); UCMP, University of California Museum of Paleontology (Berkeley); YPM, Peabody Museum, Yale University.)

METHODS

Because we are ultimately interested in footprint data, to reduce error we should only be measuring the undersides of feet (i.e., dorsal surfaces of phalanges). However, one can not always do so, for instance if a specimen is mounted, or still partially encased in rock. Therefore, many of the measurements of phalangeal and digit lengths were of top (ventral) surfaces. For each instance where both dorsal and ventral surfaces of phalanges were measured, we compared the measurements to ascertain if dorsal and ventral data could be used interchangeably. For individual phalanges, differences in dorsal and ventral measurements ranged from negligible (<5% difference, probably simply measurement error) to high (>20% difference). There does not seem to be any systematic trends in these differences: one can not generalize for a clade, for instance. Therefore, when one is interested in measurements of individual phalanges, for comparison with footprints, only dorsal measurements should be used. This is a significant finding; in those few osteological descriptions which include phalangeal measurements (most of the time, one is lucky if the *digits* are measured!), it is not stated which surface is being measured; using published osteological measurements could therefore lead to significant problems when working with footprints!

We also compared dorsal and ventral measurements for complete digits (phalangeal portions). In most cases, differences were negligible (<5% difference) and likely due to measurement error. In a very few instances, differences were much higher (15-23% differences).

For consistency, even though in this study we were only interested in lengths of digits (rather than individual phalanges), we only included in the analysis those dinosaurs with ventral surface measurements; while dorsal measurements would have been preferable (as being directly relatable to footprints), the nature of the materials was such that we had few dorsal measurements.

Because Alexander's (1976) speed equation requires us to estimate a skeletal dimension (hip height) from *trackway* data, we need to ensure that we know how our footprint measurements relate to feet. All previous studies have assumed that footprint length corresponds to the length of the phalangeal portion of digit III. However, the footprints of bipedal dinosaurs generally do not possess a pad for the metatarsophalangeal joint on digit III, so we do not know the length of the proximal phalange on that digit. In addition, the rear of the footprint is generally the pad made by the metatarsophalangeal joint of digit IV, and because metatarsal IV is always shorter than digit III, the footprint length is therefore going to be greater than simply the sum of the phalanges of digit III (Figure 2). Assuming that the phalangeal pad is made by a joint (i.e., the arthral condition) (Baird 1957), one can directly measure lengths of some pedal elements from footprints (Olsen *et al.* 1998), thus permitting direct comparisons of osteological data with data derived from footprints. The size and position of the claw in a single footprint species can be highly variable, and the length of the ungual bone can not be directly measured from footprints, because the length of the keratin sheath covering the claws is usually unknown (Rainforth 2003); therefore, in this study, we conducted our analyses twice, with claws either included or excluded.

In this study, we define *foot* length (F) as follows:

$$F = \text{digit III phalanges} + \text{metatarsal III} - \text{metatarsal IV}$$

Foot length including the claw on digit III permits comparison with previously published skeletal measurements and equations (e.g. Alexander 1976, Thulborn 1990); foot length excluding the claw on digit III provides a better comparison with footprints (Rainforth 2003). Leg length is defined here as the sum of the lengths of the femur and tibia. We exclude mt III (*contra* Thulborn 1989, 1990) because the contribution of the tarsus to leg length is often unknown: tarsal elements are small and disarticulate upon death, so many specimens are preserved without these bones.

RESULTS

We graphed various combinations of skeletal measurements and ratios in order to determine if there was a single ratio of leg length:foot length (using our definitions of leg and foot length), following Alexander (1976) and Henderson (2003), or a range of ratios, following Thulborn (1989, 1990). We would not necessarily expect to find exactly the same ratios as Alexander (1976) or Thulborn (1989, 1990), because our definitions of leg length and foot length are not quite the same as either Alexander's or Thulborn's definitions. Figure 2 plots the ratio of leg length to foot length for our specimens; the 'multiplier' of our y-axis is the factor by which FL is multiplied to obtain h.

Even though our sample size is small, several important results can be seen on these plots:

1. no single multiplier applies for all dinosaurs (*contra* Alexander 1976, Henderson 2003); the total range for bipedal dinosaurs (when claw is included in measurements) is 2.8 to 5.9. If one is unable to identify a footprint beyond 'bipedal dinosaur' (i.e., unable to ascertain if it is a theropod or ornithischian print), speed estimates could be incorrect by a factor of 2.
2. within dinosaurian groups, there is a wide range of variation in multipliers; this variation is greater than reported by Thulborn (1990) (note that Thulborn categorized 'small' dinosaurs as those with foot lengths <25 cm; on Figure 2, dinosaurs with FL<25 cm are those with leg lengths < 1 m);
3. the variation in multipliers within dinosaurian groups is independent of overall size of the individual dinosaurs (e.g., the multiplier for theropods [using foot length including claw] ranges from 2.8-4.2, regardless of animal size: both small and large animals have ratios at each end of the spectrum)

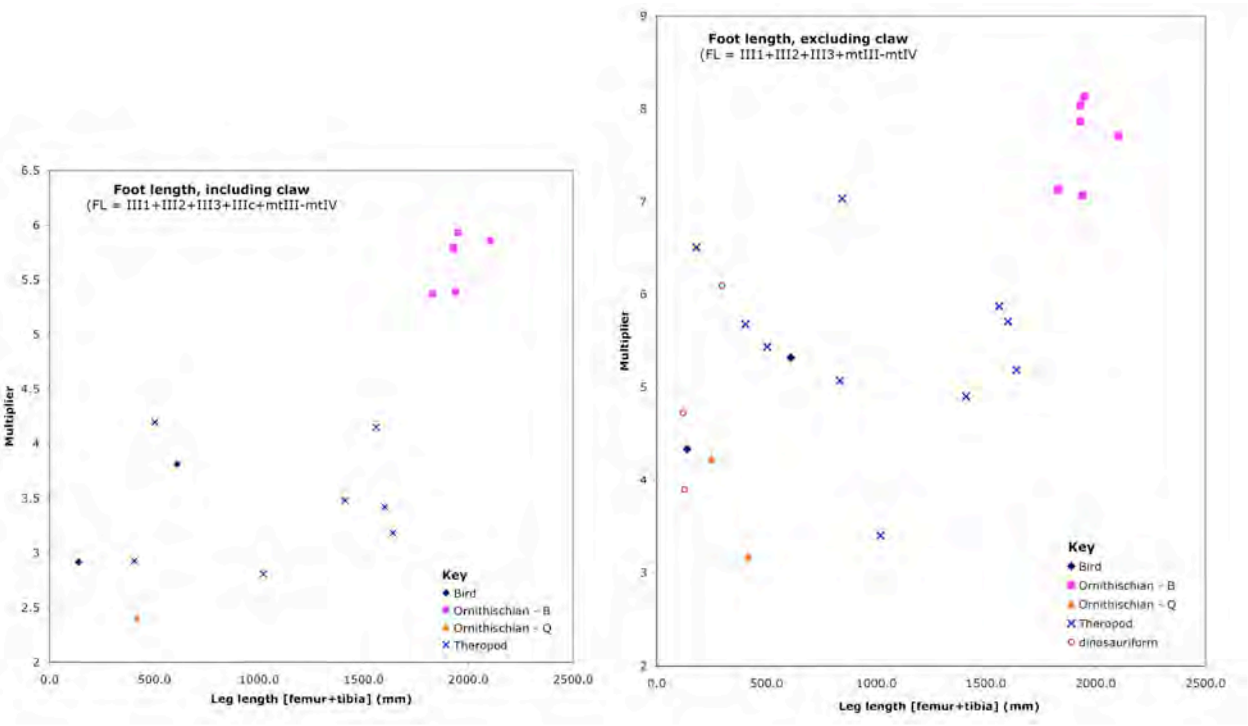

Figure 2. Ratios of leg length to foot length for various dinosaurian specimens, plotted as leg length vs. multiplier (where multiplier = h/FL). Foot length as defined here includes only that portion of the foot that is commonly preserved in footprints, in order to allow direct comparison with footprint data. Because there can be variability in claw length (due to keratin sheath on claw) and claw position in footprints, we determined the leg:foot ratios both with and without unguals (left and right graphs respectively). Several specimens were missing the ungual; the left graph allows direct comparison with previous studies, whereas the right graph, with more specimens represented, better allows variability to be examined. The one sauropod specimen was omitted from these plots; it's multiplier is 10.4 (with claw) or 25.2 (without claw). Ornithischian-B: bipedal ornithischians; Ornithischian-Q: quadrupedal ornithischians.

To compare directly with Thulborn's morphometric ratio results (Table 1), we can summarize the multipliers we obtained (for foot length including claws); at this time, we have not determined allometric equations for comparison with Thulborn's (1990) equations.

Small theropods: 2.9-4.2
Large theropods: 2.8-4.2
Small ornithopods: no data
Large ornithopods: 5.4-5.9
Small bipedal dinosaurs in general: 2.9-4.2
Large bipedal dinosaurs in general: 2.8-5.9
Birds: 2.9-3.8

We also examined Thulborn's (1990) assumption that the length of mtIII can be used in place of footprint length; this assumption was critical to Thulborn's allometric equations. Figure 3 shows that the expected footprint length for a particular dinosaur (our 'foot length', defined above) is shorter than the length of mtIII; and within each group of dinosaurs, the relationship is variable (e.g., in small theropods, footprint length is 57-77% of mtIII length; in large theropods, footprint length is 57-111% of mtIII; in large bipedal ornithischians it is 73-83%, and in the sauropod, 50%). Thus, it does not seem reasonable to use footprint length as a proxy for mtIII length, and therefore, the allometric equations provided by Thulborn (1990) are imprecise.

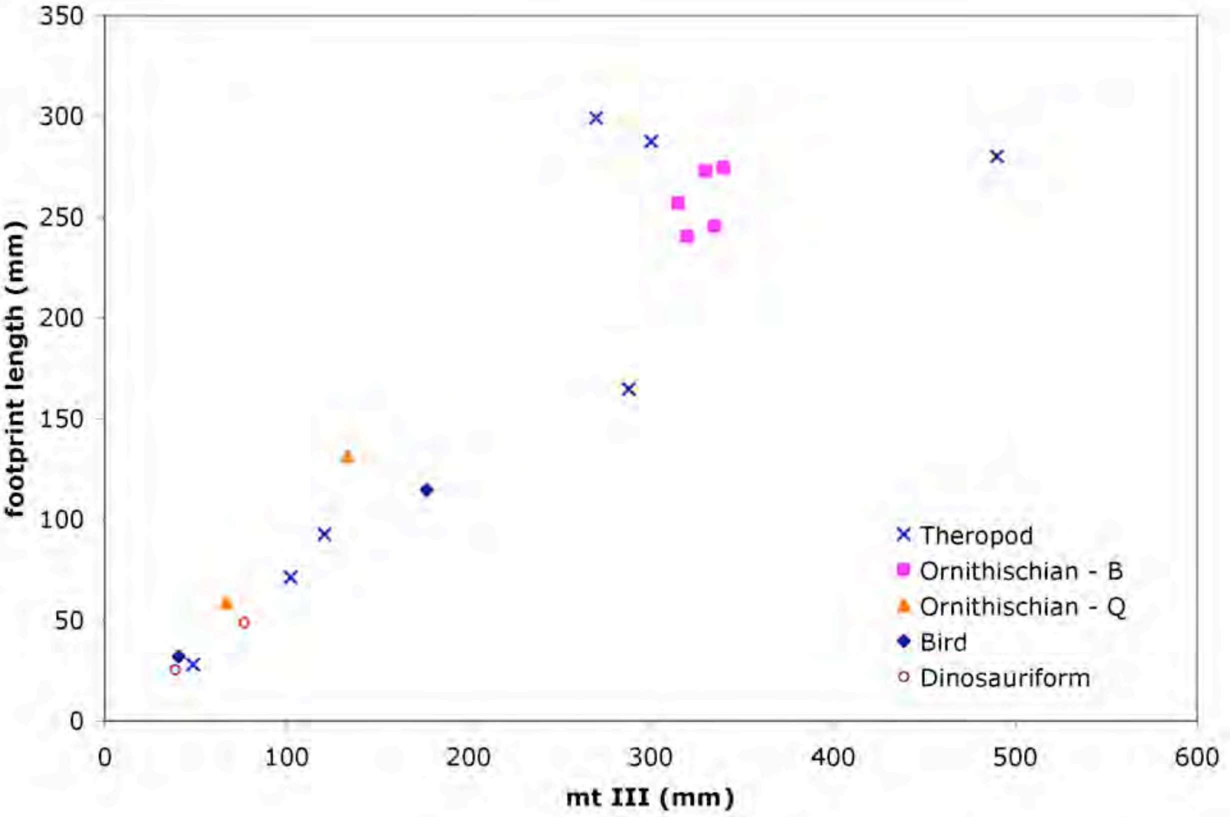

Figure 3. Relationship between length of mt III and foot length (as defined herein, i.e., that portion of the foot that makes a footprint).

PRELIMINARY CONCLUSIONS

With the caveat that our sample size is small, we can draw the following conclusions:

- there is no simple relationship between 'hip height' and 'foot length' (*contra* Alexander 1976, Henderson 2003) when one uses measurements that limit the number of assumptions about these metrics;
- mtIII length is not a good predictor of footprint length (and vice versa)

These findings have major implications for estimates of dinosaur speeds from trackway data; because there is no reliable way to estimate hip height from footprint length, either using morphometric or allometric equations, speed estimates can be off by a factor of 2 or more.

FUTURE WORK

Ongoing and future work will further address the three questions posed above ('This Study'). One line of study will be to examine the variability in *h*:*FL* ratio within individual species, in particular focusing on the ratios for different size (age) individuals; simple observation on individuals indicate allometric growth patterns. The degree of variability will then enable judgments to be made concerning these ratios for different size classes of footprints; for a footprint of a particular size, we can not ascertain if it was made by a large individual of a small species, or a small representative of a large species. We will also examine whether the range of ratios for a particular group of dinosaurs remains constant through time, or if it varies over time (as the clade evolves). If there is a change over time, then even though we will not know which species (or genus) within a clade made a particular footprint, the age of the footprint will enable us to narrow down the *h*:*FL* ratio and thus get a better estimate of dinosaur speed.

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ICHNOTAXONOMIC UPDATES FROM THE NEWARK SUPERGROUP

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ABSTRACT

The Newark Supergroup (Late Triassic – Early Jurassic) of eastern North America is world-famous for it's fossil footprint assemblages. Footprints are the most common tetrapod fossils from these strata. The field of ichnology owes it's existence to the pioneering work of Edward Hitchcock who, beginning in the 1830s, named and described Newark Supergroup footprints from the Connecticut Valley (Hartford and Deerfield basins), primarily from the Early Jurassic strata. These footprints are dominantly dinosaurian in origin, including several ichnogenera attributable to theropods. Subsequent studies elsewhere in the Supergroup have resulted in a few additional ichnogenera and ichnospecies being discovered, including *Apatopus* and *Brachychirotherium* from Milford, NJ. Whilst the nomenclature of the Connecticut Valley prints has been addressed (Rainforth 2005), the ichnotaxonomy (relationships between footprints) has not been revised in detail. It is recommended here that not only the synonymy of *Grallator* and *Anchisauripus* with *Eubrontes* be upheld, but in addition, the remaining prints from the Connecticut Valley attributed to theropods should also be synonymized with *Eubrontes* because they are only behaviorally (rather than osteologically) distinct. Examination of two ichnogenera attributed to crurotarsans have also resulted in nomenclatural and ichnotaxonomic revisions. Some of Hitchcock's ichnospecies of *Batrachopus* are synonymized; *Shepardia* and *Comptichnus* are synonymized with *Batrachopus*; and Lockley *et al.'s* (2004) synonymization of *Selenichnus* with *Batrachopus* is rejected. *Apatopus* is found to only occur at one location in the Newark Supergroup (Milford NJ); specimens from other localities and stratigraphic horizons were mis-identified and are brachychirotheres.

INTRODUCTION

Ichnology dates to the 1830s with the pioneering work of the Rev. Edward Hitchcock, Professor and later President of Amherst College (Amherst, Mass.). Over the ensuing 30 years, Hitchcock acquired thousands of rock slabs bearing fossil footprints, almost all of which are still housed in the Hitchcock Ichnological Collection at the Amherst College Museum of Natural History. Most of these specimens come from the earliest-Jurassic strata of the Connecticut Valley region of Connecticut and Massachusetts (i.e., Hartford and Deerfield basins), and include footprints of dinosaurs, lacertilians, and crurotarsans. By the late nineteenth century, similar footprints were also known from elsewhere in the eastern U.S., notably New Jersey, from rocks of Late Triassic to earliest Jurassic age (Figure 1).

The Connecticut Valley material includes the key reference material for most Early Jurassic ichnotaxa. Of all the fossil footprints from the Newark Supergroup, it is these dinosaur footprints that have received the most attention by professionals and amateur collectors alike. However, until recently, the nomenclature of the prints was encumbered with objective and subjective synonyms as well as homonyms, in part because type specimen identities had been confused; Rainforth recently (2005) resolved most of these issues. This paper will provide an overview of some of the ichnotaxonomic and nomenclatural changes of that and ongoing studies.

Abbreviations: AC, Amherst College Museum of Natural History; LC, Lafayette College Geology Department.

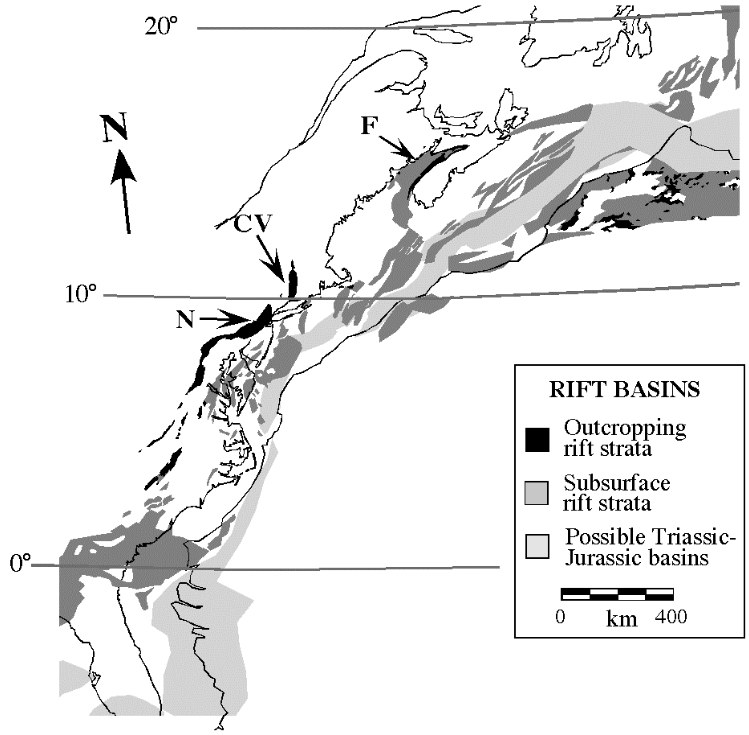
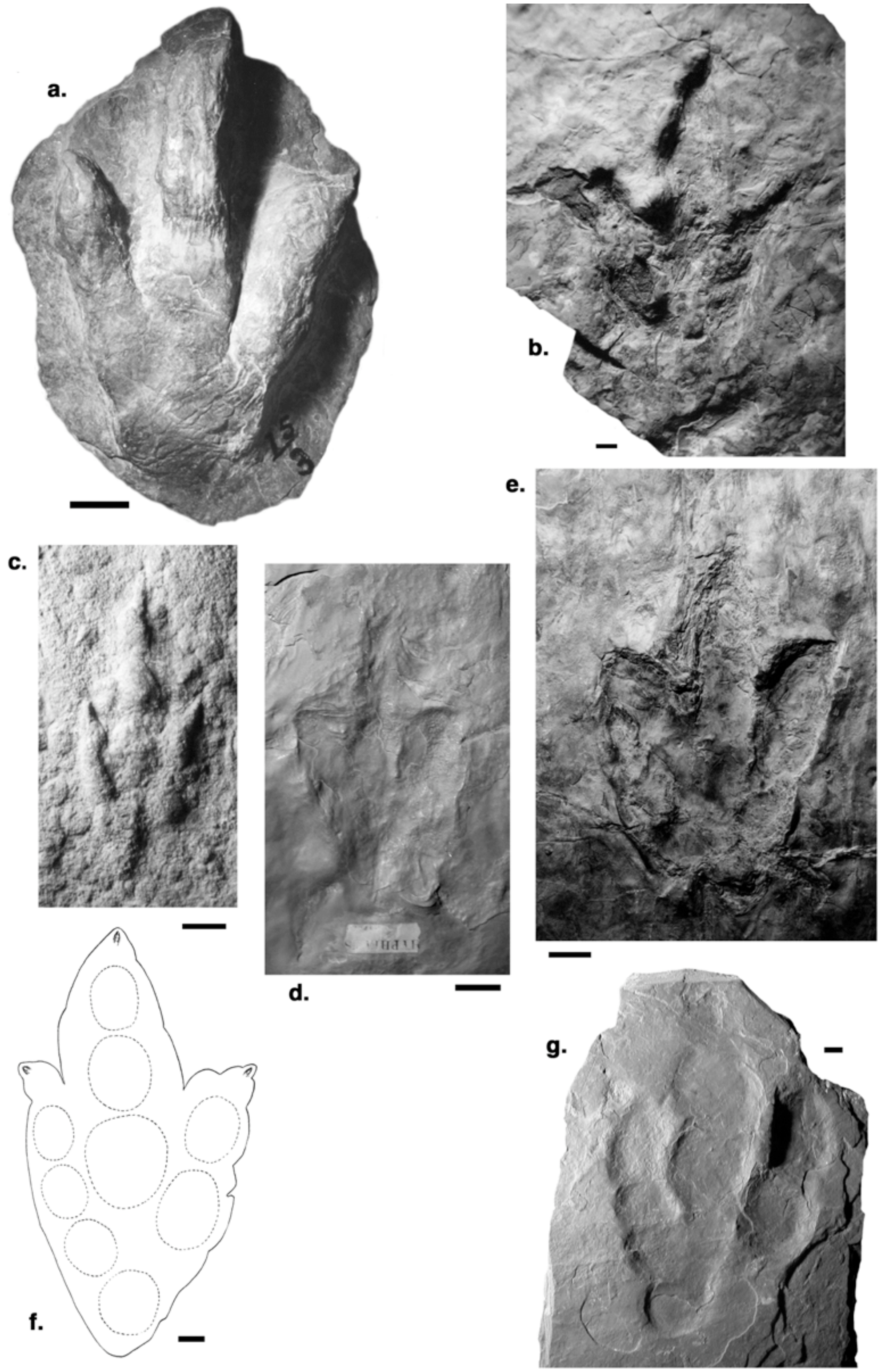


Figure 1. Late Triassic – Early Jurassic rift basins, eastern North America and northwestern Africa, in their ~200 Ma configuration. Light gray lines indicate paleolatitude; North arrow is present-day north for the Connecticut Valley (CV) region. The four basins bearing significant footprint assemblages are the Deerfield and Hartford basins (CV), Newark (N), and Fundy (F) basins. (Modified from LeTourneau and Olsen 2003 and Rainforth 2005.)

Figure 2 (facing page). Type specimens of type species of the brontozoid ichnogenera. a) AC 15/3, lectotype of *Eubrontes giganteus* from Mt. Tom, Northampton, Mass.; b) AC 4/6, lectotype of *E. sillimani* (= *Anchisauripus dananus* Lull 1904) from Chicopee Falls, Mass.; c) AC 4/1a, fourth print in lectotype of *E. cursorius* (*Brontozoum parallelum* E. Hitchcock 1847), from the Moody homestead, South Hadley, Mass.; d) AC 1/3, third print in lectotype trackway of *E. fieldi* (*Hyphepus fieldi* Hitchcock 1858), from the Lily Pond, Gill, Mass.; e) AC 9/10, third print in lectotype trackway of *E. caudatus* (*Gigandipus caudatus* Hitchcock 1856), from the Lily Pond, Gill, Mass.; f) BSNH 12857, holotype of *Otouphepus magnificus*, from Gill, Mass.; g) AC 31/85, lectotype of *E. lyellii* (*Ornithoidichnites lyellii* E. Hitchcock 1843, *Fulicopus lyellianus* E. Hitchcock 1845*,* from Turners Falls, Mass. Scale bars represent 50 mm (in a and e), 10 mm (in b, c, f and g), and 20 mm (in d).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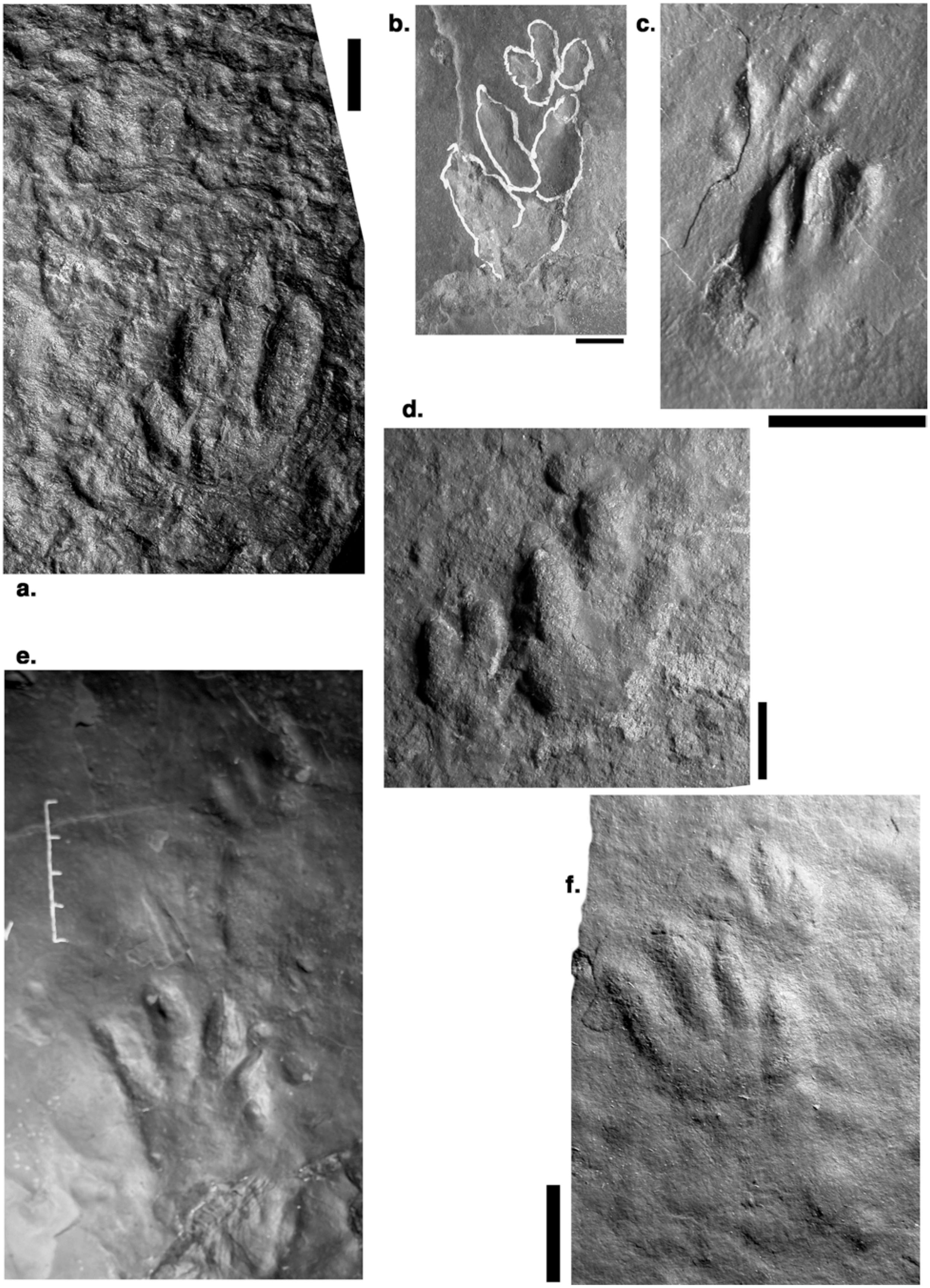
THE BRONTOZOID ICHNOTAXA

Three common ichnogenera from the Newark Supergroup are *Eubrontes* Hitchcock 1845 (Figure 2a), *Anchisauripus* Lull 1904 (Figure 2b), and *Grallator* Hitchcock 1858 (Figure 2c). From 1836 when Hitchcock first named footprints (in which they were all placed in the ichnogenus *Ornithichnites*, with *O. giganteus* the type ichnospecies), through 1858, specimens currently referred to these three different ichnogenera were all considered congeneric, and were placed in the ichnogenus *Brontozoum* Hitchcock 1847. When Hitchcock (1858) erected the name *Grallator*, he did so for those ichnospecies of *Brontozoum* that were small, with relatively long strides. The ichnogenus *Anchisauripus* was erected for ichnospecies formerly (Hitchcock 1858) remaining in *Brontozoum*, that were intermediate (in footprint size and stride length) between *Grallator* and *Eubrontes* (which is the objective senior synonym of *Brontozoum*, as recognized by Hay [1902]; it's type ichnospecies is *O. giganteus*), bore a hallux impression, and was made by *Anchisaurus* (Lull 1904).

One can immediately see two problems with Lull's (1904) concept of *Anchisauripus*: first, one can not define a footprint based upon it's presumed trackmaker (which, in this case, was incorrectly identified; *Anchisaurus* is a prosauropod, whereas subsequent analyses (Lull 1915, and most subsequent studies) determined that theropods were the trackmaker); and second, there is not a single example of *Anchisauripus* that actually bears a hallux impression (Rainforth 2005). Finally, the original character distinguishing *Grallator* from *Brontozoum* (*Eubrontes*) was size, which is also the only remaining character that separates *Anchisauripus* from *Grallator* and *Eubrontes*. However, as noted by Olsen (1980), there are no discrete size classes for these ichnogenera, but rather a continuum of sizes; morphological differences follow trends across the entire size range, and thus it is not possible to separate *Grallator*, *Anchisauripus* and *Eubrontes* by anything other than an arbitrarily-determined cut-off in size (Olsen 1980, Olsen *et al.* 1998, Smith and Farlow 2003). Therefore, Olsen (1980) subjectively synonymized the three ichnogenera, retaining *Grallator* as the valid ichnogenus because the type specimen of *O. giganteus,* the type ichnospecies of *Eubrontes* (the senior synonym), was missing at that time. Rainforth (2005) followed Olsen's (1980) synonymy, but using *Eubrontes* as the valid name.

In a recent review of the Connecticut Valley ichnotaxa, Rainforth (2005) suggested that in addition to synonymizing *Grallator* and *Anchisauripus* with *Eubrontes*, several other less well known ichnogenera should also be synonymized with *Eubrontes*. *Fulicopus* (Figure 2g) is simply a sitting trace of a mid-size *Eubrontes*, with ischial, metatarsal and manus impressions; *Gigandipus* (Figure 2e) and *Hyphepus* (Figure 2d) are large and small *Eubrontes* with tail traces and hallux impressions, probably made by a *Eubrontes* trackmaker leaning further back than usual (Rainforth 2004); *Otouphepus* (Figure 2f) is merely a poorly preserved small *Eubrontes*. These four ichnotaxa are thus either behavioral variants of *Eubrontes* (*Fulicopus, Gigandipus, Hyphepus*), or poorly preserved examples (*Otouphepus*); in all cases, the basic morphology is that of *Eubrontes* (of various sizes) (Rainforth 2004, 2005).

Figure 3 (facing page). Type specimens of Hitchcock's six species of *Batrachopus*. a) AC 41/51, pes-manus couplet on holotype slab of *Batrachopus deweyi*, from Turners Falls, Mass.; b) AC 26/21, lectotype of *Batrachopus bellus* (*Apatichnus bellus* Hitchcock 1858), from Turners Falls, Mass.; c) AC 46/3, lectotype of *Batrachopus gracilior* (*Anisopus gracilior* Hitchcock 1865) from the Turners Falls area (Mass.); d) AC 20/4, holotype of *Batrachopus parvulus* (*Ornithoidichnites parvulus* Hitchcock 1841); e) AC 21/1, holotype of *Batrachopus dispar*, from the Lily Pond quarry (Gill, Mass.); f) AC 32/45, lectotype of *Batrachopus gracilis* (*Anisopus gracilis* Hitchcock 1848), from Turners Falls, Mass. Scale bars represent 10 mm (in a, b, c, d, f); white scale bar in e represents 4 cm.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CRUROTARSAN ICHNOGENERA

Batrachopus

Batrachopus, first described by Edward Hitchcock (1843, 1858), includes six ichnospecies (Rainforth 2005) (Figure 3). Olsen & Padian (1986) synonymized *B. bellus, B. gracilior* and *B. gracilis* with the type species, *B. deweyi*, but those authors had not examined the holotype of *B. deweyi*; their synonymization was rejected by Rainforth (2005). Current studies separate the species of *Batrachopus* into two groups, gracile and robust. Gracile *Batrachopus* have relatively long slender digits which do not contact each other along their length; robust forms have relatively short wide digits which contact each other along their length. Examples of both morphologies occur as well-preserved tracks in similar substrates, leading me to consider that these groups are not an artifact of kinematics, taphonomy, or substrate conditions. I believe *B. parvulus* can be synonymized with the type species, *B. deweyi*; and tentatively, *B. gracilior* can be synonymized with *B. gracilis* (although *B. gracilior* is not terribly well preserved). In addition, a specimen (AC 51/18) previously catalogued as *Arachnichnus dehiscens* is actually referable to *B. bellus* (although the type material of *A. dehiscens* is indistinct but not referable to *Batrachopus*). The ichnospecies *Shepardia palmipes* (which is the type and only ichnospecies of that ichnogenus; Figure 4a) is synonymized with *Batrachopus gracilis*. Finally, *Comptichnus obesus* (the type and only ichnospecies of the ichnogenus; Figure 4b) is also referable to *Batrachopus*; the lectotype specimen (and thus the ichnospecies) is identified as *B. bellus*, and the paralectotype specimen is referred to *B. deweyi*.

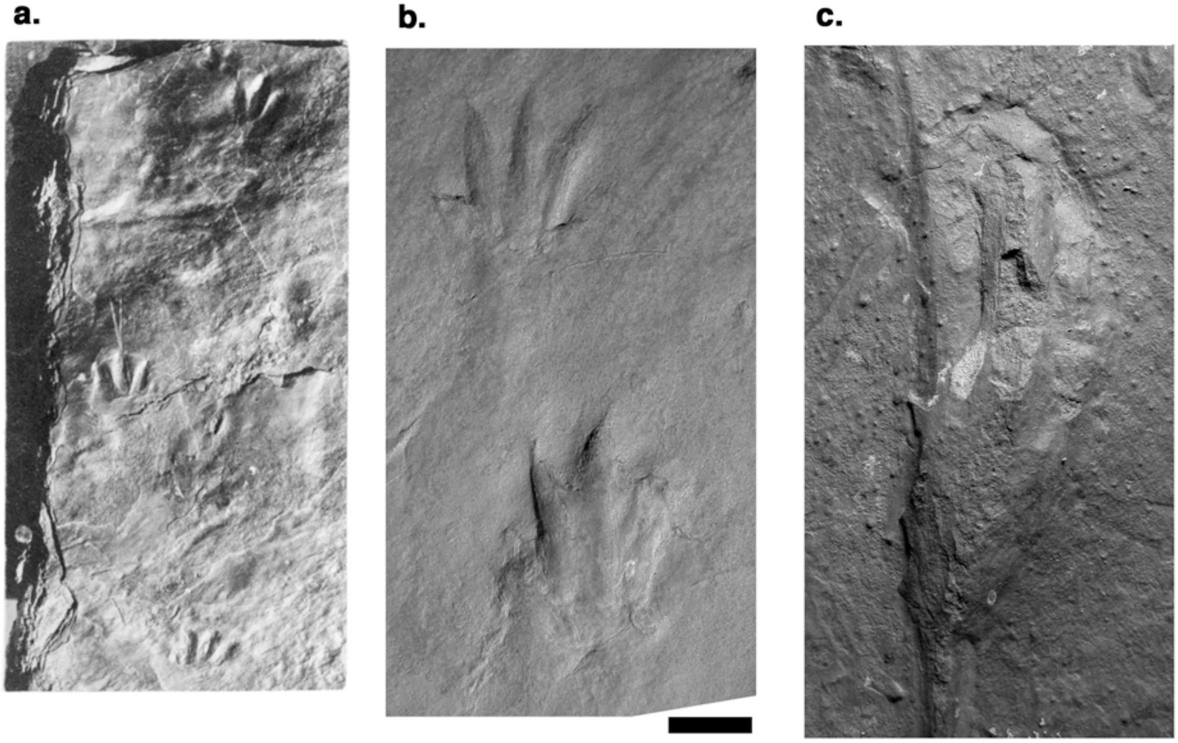


Figure 4. Type specimens of ichnospecies herein referred to (a-b) and removed from (c) *Batrachopus*. a) AC 55/5, lectotype of *Comptichnus obesus*, from the Lily Pond quarry, Gill, Mass. (photograph from Hitchcock 1865); b) AC 60/76, probable holotype of *Shepardia palmipes* (scale bar represents 10 mm); c) AC 42/7, track in lectotype trackway of *Selenichnus falcatus*, from the ferry at Turners Falls (print is appx. 50 mm long).

Lockley *et al.* (2004) recently took umbrage that Olsen and Padian (1986), in their extensive synonym lists for *Batrachopus*, did not include *Selenichnus* as a (subjective junior) synonym. Lockley *et al.* (2004) claim that specimens of *Selenichnus* from the Early Jurassic of southern Utah grade insensibly into *Batrachopus*-type morphologies (and thus, because *Batrachopus* is considered crocodylomorph, *Selenichnus* is also identified as a crocodylomorph track). Examination of the materials in question shows that (1) Lockley *et al.* (2004) have mistaken the type materials of *Selenichnus* to be quadrupedal trackways with tetradactyl pes, whereas all of the specimens – type and referred - are clearly a bipedal tridactyl trackway (and therefore almost certainly made by theropods; they can not be crocodylomorph in origin; Figure 4c), and (2) the specimens from southern Utah are indeed quadrupedal trackways with bipedal pes – and thus can not be referred to *Selenichnus*. Thus, the subjective synonymization of *Selenichnus* with *Batrachopus* by Lockley *et al.* (2004) is rejected here.

From the cladistic methodology of trackmaker identification (comparing characters in the footprints with characters of possible trackmakers; Figure 6), the trackmaker is confirmed as a crocodylomorph (following Olsen and Padian 1986).

Apatopus

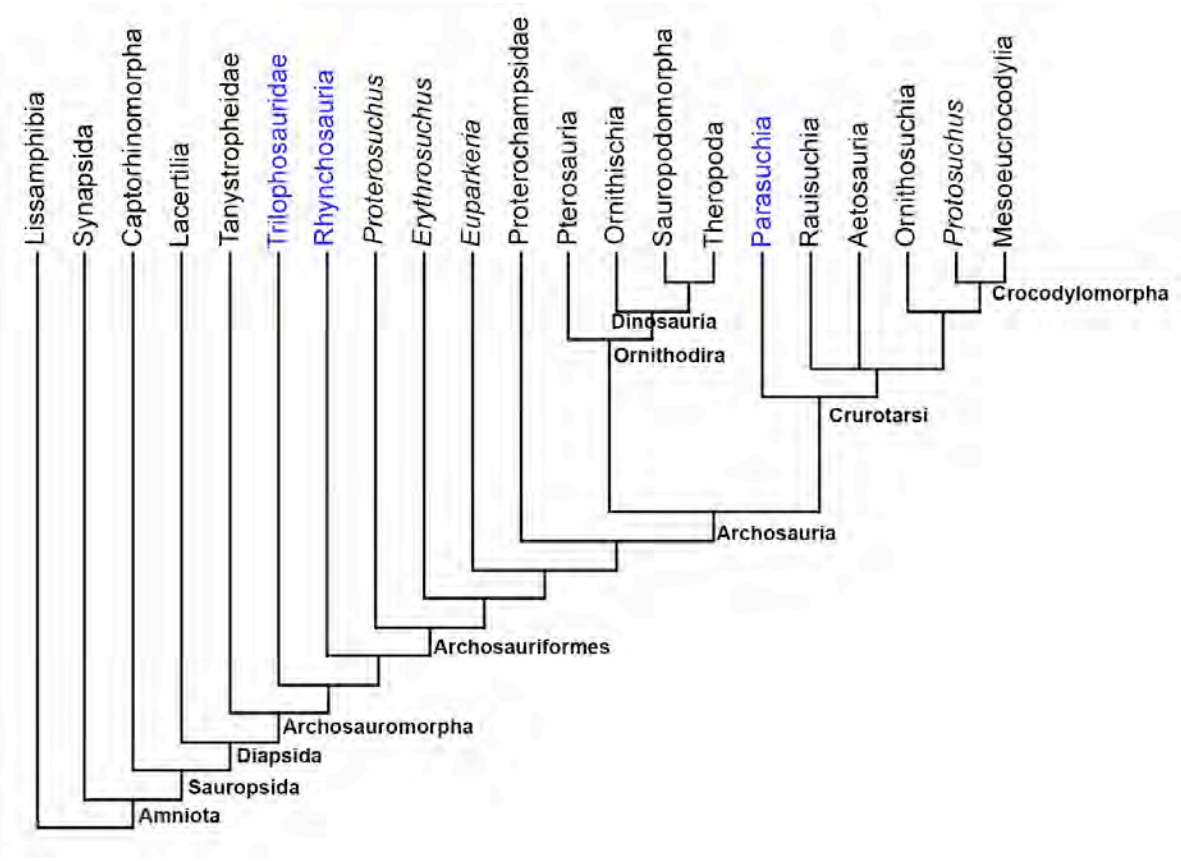
Apatopus was first described from eastern North America (Bock 1952), but has received no scrutiny since the 1950s. *Apatopus lineatus* is the only ichnospecies of this ichnogenus (Figure 7). A redescription of the holotype and paratypes, all from a single quarry in Milford, NJ, enabled comparison with specimens referred to this ichnotaxon from other localities (of slightly younger ages within the Late Triassic) in New Jersey (Osborne and Rainforth 2006). The significant results from this study are that all referred specimens from localities other than the type locality of Milford NJ have been misidentified, and are actually brachychirotheres (but not all are referable to *Brachychirotherium*; a new ichnogenus needs to be erected for some of this material). This has important implications: the stratigraphic (temporal) and geographic range of the ichnotaxon is now extremely limited, being known from a single locality in the Newark Supergroup (cf. Olsen et al. 2002). However, the ichnotaxon is known from similar aged strata of the Colorado Plateau (Foster *et al*. 2003).

From the cladistic methodology of trackmaker identification, the trackmaker is identified as most likely being a phytosaur (parasuchid) (Figure 6).

SUMMARY

Recent investigations have cut through the nomenclatural quagmire of Early Jurassic ichnological nomenclature. Careful examination of type specimens show:

1) most footprints attributable to theropods should be referred to the ichnogenus *Eubrontes*; ichnospecies-level investigations are ongoing;
2) *Batrachopus*' ichnotaxonomy can be simplified from Hitchcock's 6 species, but the synonymies of Olsen and Padian (1986) are not upheld here;
3) The ichnogenus *Apatopus* is of extremely limited geographic and stratigraphic extent, known from a single locality in the Newark Supergroup. Because its range is unknown, the ichnogenus has limited biostratigraphic and biogeographic usefulness.



	Character #				
Taxon	1	2	3	4	5
Lissamphibia	0	0	0	0	0
Synapsida	1	0	0	0	0
Captorhinomorpha	0	0	0	0	0
Lacertilia	0	0	0	0	0
Tanystropheidae	0	0	0	0	0
Trilophosauridae	0	0	0	0	0
Rhynchosauria	0	0	0	0	0
Proterosuchus	0	0	0	0	0
Erythrosuchus	0	1	0	0	0
Euparkeria	1	1	0	0	0
Proterochampsidae	1	1	1	1	0
Pterosauria	1	1	1	1	0
Ornithischia	1	1	1	1	0
Sauropodomorpha	1	1	1	1	0
Theropoda	1	1	1	1	0
Parasuchia	0	1	1	1	0
Rauisuchia	1	1	1	1	0
Aetosauria	1	1	1	0	0
Ornithosuchia	1	1	1	0	0
Protosuchus	1	1	1	0	1
Mesoeucrocodylia	1	1	1	1	1

Figure 6 (facing page). Top: consensus cladogram of Late Triassic/Early Jurassic taxa; taxa in blue are candidates for the *Apatopus* trackmaker. Bottom: data matrix. Characters are: 1 - longest digit in pes & manus is IV (0), III (1); 2 – pedal digit V has 4 (0) or less than 4 (1) phalanges; 3 – pedal digit V is longer (0) or shorter (1) than digit I; 4 – pedal digit V has (0) or lacks (1) phalanges; 5 – pedal digit IV has 5 (0) or 4 (1) phalanges. Data from Brochu 2001, Gower and Wilkinson 1996, Juul 1994.

Figure 7. *Apatopus lineatus* holotype, LC S490. Scale bar represents 20 mm.

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GEOLOGY OF GREAT NOTCH, NEW JERSEY: A TEACHERS FIELD-GUIDE TO DINOSAURS, BASALT FLOWS, AND SPIRIT RIVER

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ABSTRACT

Since 1974, this author has been collecting dinosaur tracks and zeolites at three quarries near Great Notch. The only possible river course (Spirit River), preserved by pillow lava flows up to 3 m thick, was excavated in the Houdaille Quarry located in Little Falls, New Jersey. Besides the amethyst and smoky quartz, agate, red-orange stilbite and yellow calcite within the pillow lava-basalt, there is, below the basalt, sandstone and shale containing the molds and casts of thousands of tracks of dinosaurs, other reptiles, and insects, as well as plant macrofossils. . The fossil tracks are only abundant within about two meters below the overlying basalt flow. These strata are dated to the earliest Jurassic.

INTRODUCTION

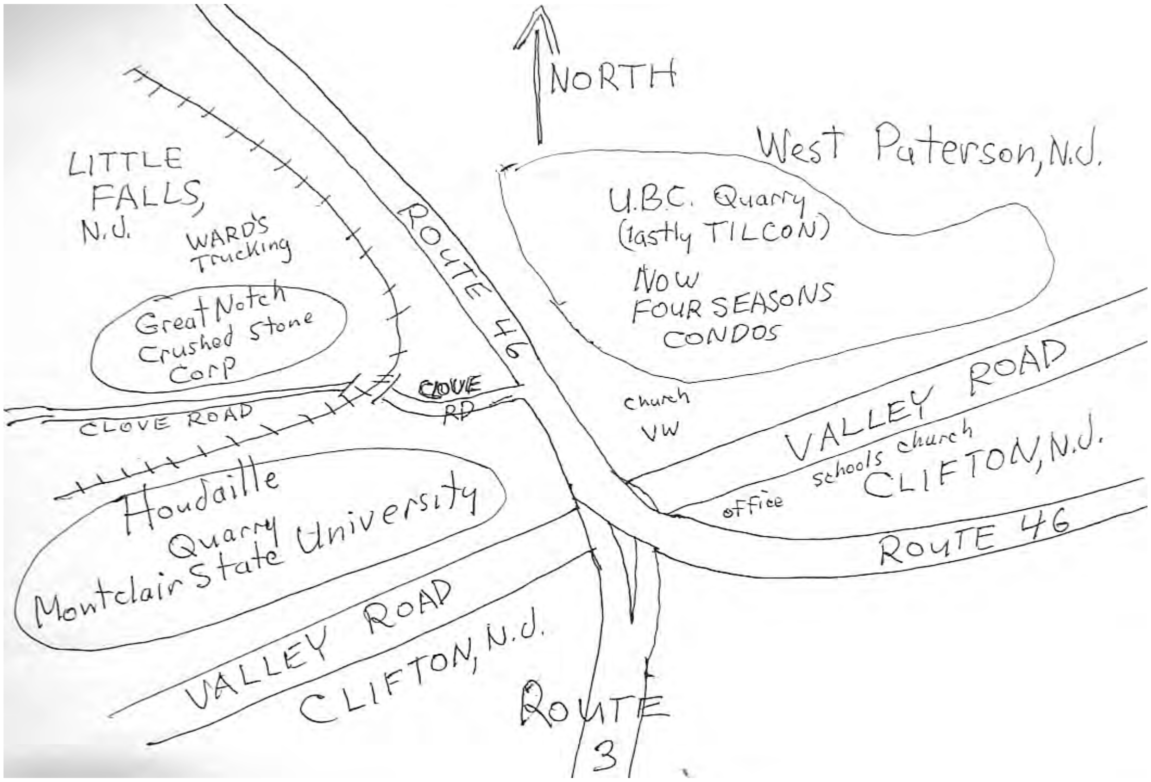

Figure 1. Field sketch of the three Great Notch crushed basalt quarries.

No one may collect rocks or fossils without difficult to obtain permission from quarry owners. However, some collectors find a way. If confrontation with security officials is to be avoided then trespassing is not advisable. Currently, the quarries of Great Notch (Figure 1) are no longer mined for trap rock and are instead part of Montclair University and a truck warehouse company on the south, and an apartment complex developer (Four Seasons condos, UBC quarry) to the north. The last blasting with rock drills and explosives on any large scale was done in 2006. The Passaic Formation sandstones and conglomerates exposed in the Great Notch quarries more than two meters below the Orange Mountain Basalt are predominantly cyclical lacustrine layers that are devoid of any fossil traces other than invertebrate trails.

GEOLOGIC TOPICS OF INTEREST AT GREAT NOTCH

- Agate – 1-4 mm size agates concentrated in a layer near the top of the first basalt flow, and half-moon vesicles (hollow shapes) lined with prehnite.
- Basalt lava – hundreds of meters thick with vesicles (bubbles) some of which were later filled with minerals (amygdules).
- Diapirs of basalt located in the lower colonnade of Orange Mountain Basalt flows as described by Laskowich and Puffer (1990) contain very large gas vesicles lined with beautiful green prehnite and chalcopyrite. Instead of the normal vertical cooling cracks in the basalt called columnar jointing, diapirs are surrounded by jointing called platy-prismatic, resulting in relatively flat elongated rectangular slabs.
- Dinosaur footprints – 3 cm to 30 cm long with up to 3 m between tracks indicating running dinosaurs.
  - The most common size of three-toe dinosaur track is about 15 cm, and is called *Anchisauripus* (Figure 2). They were probably made by dinosaurs resembling the Late Triassic *Coelophysis* found at Ghost Ranch, New Mexico. A typical (but rare) manus (hand) print appears in Figure 3.

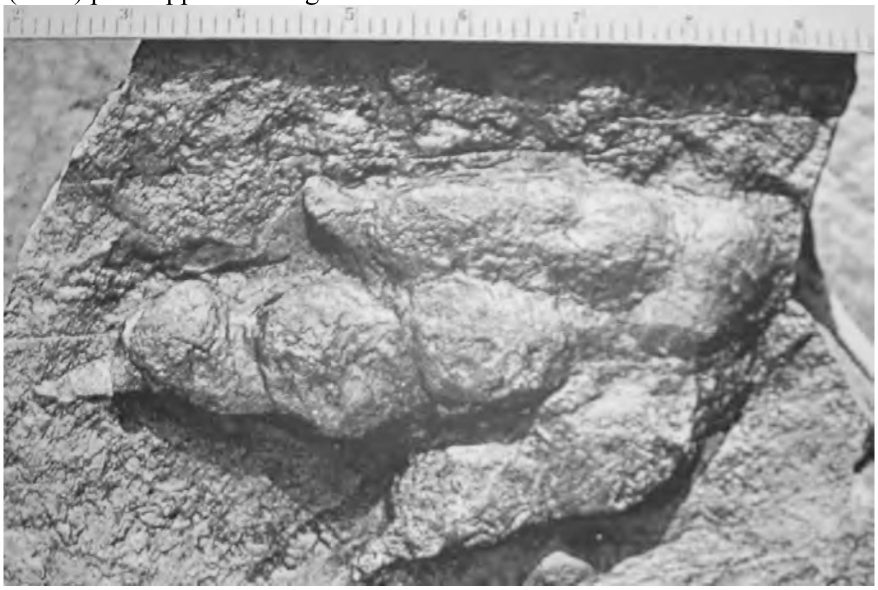

Figure 2. A 17 cm *Anchisauripus* track from the UBC quarry.

Figure 3. An *Anchisauripus* manus (hand) print from the UBC quarry

Figure 4. A juvenile (baby) *Grallator* track. From the UBC quarry.

  - Smaller three-toed tracks which may be juveniles were found, as small as 4 cm long (Figure 4); these are named *Grallator*.
  - The large 25 to 40 cm tracks are called *Eubrontes*, likely made by an theropod dinosaur resembling *Dilophosaurus*. (Note that the names of dinosaurs are independent of the names of the tracks, because we can never be certain what species of dinosaur made a particular footprint.) Footprints that were about 30 cm long were found in the 1980's that were separated by 3 m, indicating a running dinosaur (15 to 20 mph? Hot-blooded!)

Figure 5. A lava pause exposed as a low angle discontinuity along the middle of the wall, UBC quarry.

- Lava Pause (Figure 5) - Exposed on the west wall of the West Paterson quarry is a chilled lava surface that is interpreted as a contact where a lower flow paused before an overlying flow extruded onto it. There is a millimeter of agate in between and within the chilled lava layers. The reason for the lava pause may have been a slowing of lava from the vent itself, or from a quake-related shift in the Newark Basin's shape. Or, more likely, the pause was due to the lava having to fill the SPIRIT RIVER basin to the south and west. (Spirit River alludes to name of Ghost Ranch, New Mexico, the site of the *Coelophysis* mass burial). We know there was a shallow river running roughly from northeast to southwest through Montclair State University (between Yogi Berra stadium, where dinosaurs played first, and the Floyd Ice Arena). PILLOW LAVA marked the places where lava encountered water in sufficient quantity to form the pillow shapes, up to 8 feet thick, above the dinosaur footprints in the sediments below. It is known that the pillow lava was formed in shallow water due to the very frothy and bubbly nature of the lava (the bubbles are called amygdules, for their almond shapes). The lava paused as it took more time to fill the river basin to the south and west, before continuing north to Paterson. This lava flow was only the first of two or three flows which make up the First Watchung, the Lenape Indian name for the First Ridge, and was at least 120 feet thick. (Note that all the strata here dip to the north-west about 10 degrees.)

- Insects - Flying or hopping insects with trails.
- Lyme disease from ticks that are common in grass and weeds that grow in Great Notch quarries – Lyme disease can be a horror for those who ignore the symptoms of red to bulls-eye rash, headaches, sometimes severe, flu-like symptoms, joint pain facial paralysis, cardiac complications, loss of hearing and damage to the optic nerve. Lyme disease can be prevented with vaccinations or avoided with repellent and skin examination for ticks.
- Magnetic deviation – The magnetite in the Orange Mountain basalt aligned itself with the prevailing magnetic field of the earth as it crystallized 200 million years ago. A compass held close to some basalt exposures will show major variations in compass heading and can swing a full 80 to 90 degrees within a meter of exposed rock.
- Normal faults with 10-20 m displacements.
- Pahoehoe lava has been found up to 2 m above the base of the flows. These are smooth to ropy and stringy-surfaced surfaces that formed as lava had a chance to cool and form a hard surface before being covered by more lava. The pahoehoe lava is rare and difficult to recognize.
- Plant fossils generally occur as impression of stems including horsetail rushes (Figure 6).and small branching plants (Figure 7). Footprints are absent where plant molds and casts are present. In only one instance do I recall a 13 cm 3-toe track upon a surface where hollow stems were growing in place, straight up through the strata, but never where the reeds were pushed over and lying flat.

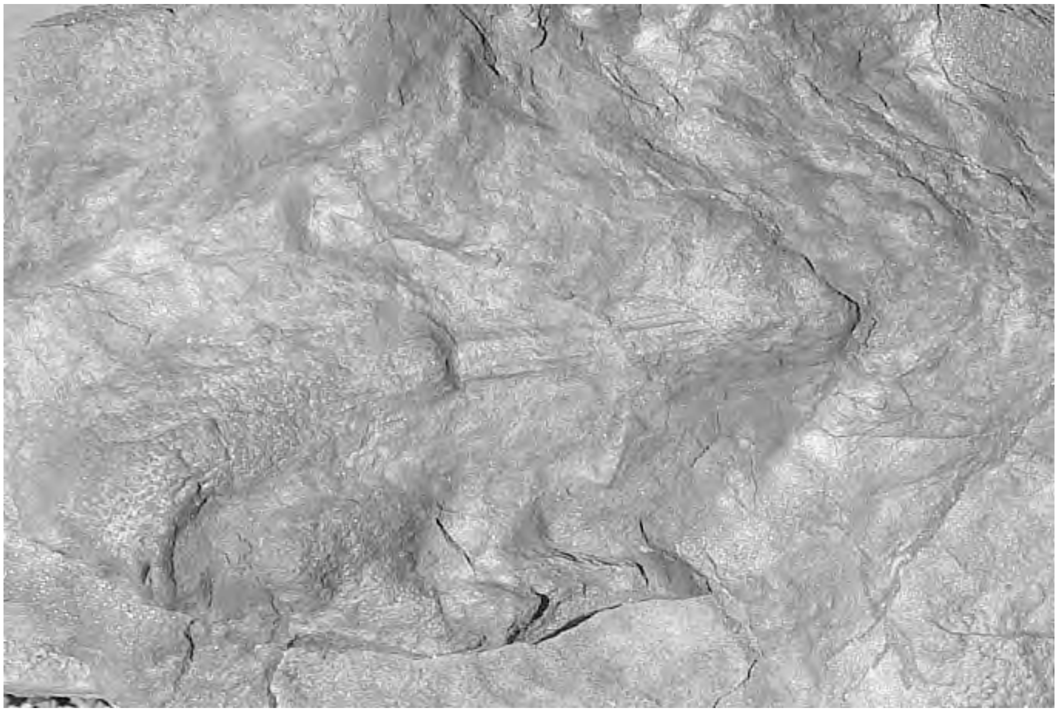

Figure 6. A horsetail fossil from the UBC quarry.

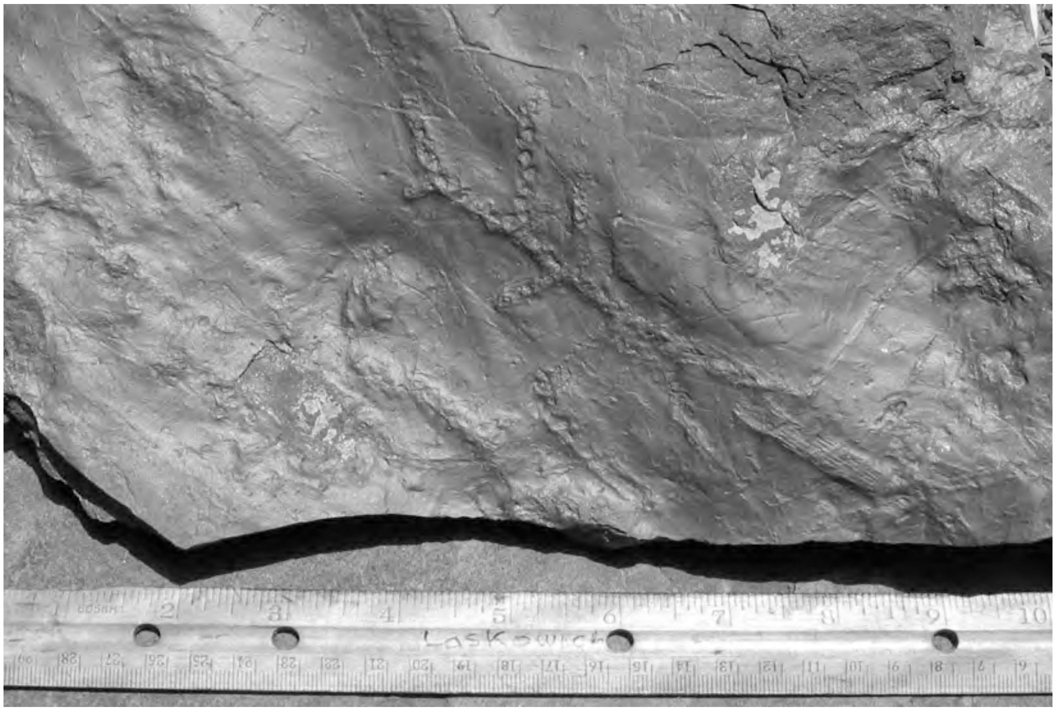

Figure 7. Small branching plant fossil from the UBC quarry.

- Great Pink Pearl – In 1857 Jacob Quackenbash, a Paterson carpenter, discovered a fresh water pearl in a mussel taken from Notch Brook near a restaurant at Rt. 46 and Clove Road, Little Falls near Montclair . The large pink pearl was sold to Tiffany's for $1,500. It was later set in the crown of Empress Eugenie of France, the wife of Napoleon III. Approximately $15,000 worth of pearly were taken form Notch Brook in 1857 (The New Jersey Almanac, 1963) Fresh water oysters were made extinct in many streams from Arkansas to New England.
- Plant pollen - Pollen is found in two lenses of grey shale located near the base of the Orange Mountain Basalt, amounting to no more than 12 cubic meters of material was analyzed for fossil plant pollen by Bruce Cornet (1977). This material was the basis for changing the formerly Triassic designation of the Orange Mountain Basalt to the current Jurassic classification. The second of the two lenses of grey shale has not been analyzed, even though it was found over 3 m deeper and had carbonized plant leaves and stems several cm wide and 45 cm long.
- Prehnite – jade green, zeolites (including stilbite), yellow calcite, quartz (including amethyst and smokey quartz. Green prehnite "fingers" are found up to 10 cm long. Inside each finger are a hollow rectangular mold that the prehnite crystals grew upon, before they dissolved as described by Laskowich (1977) and Puffer and Laskowich (1984). Above and beside pillow lava with stilbite and heulandite, there are areas where prehnite followed by calcite is common. Prehnite typically forms in botryoidal masses that can cover a few square meters of area or much less commonly can appear like green marbles. (Figure 8).

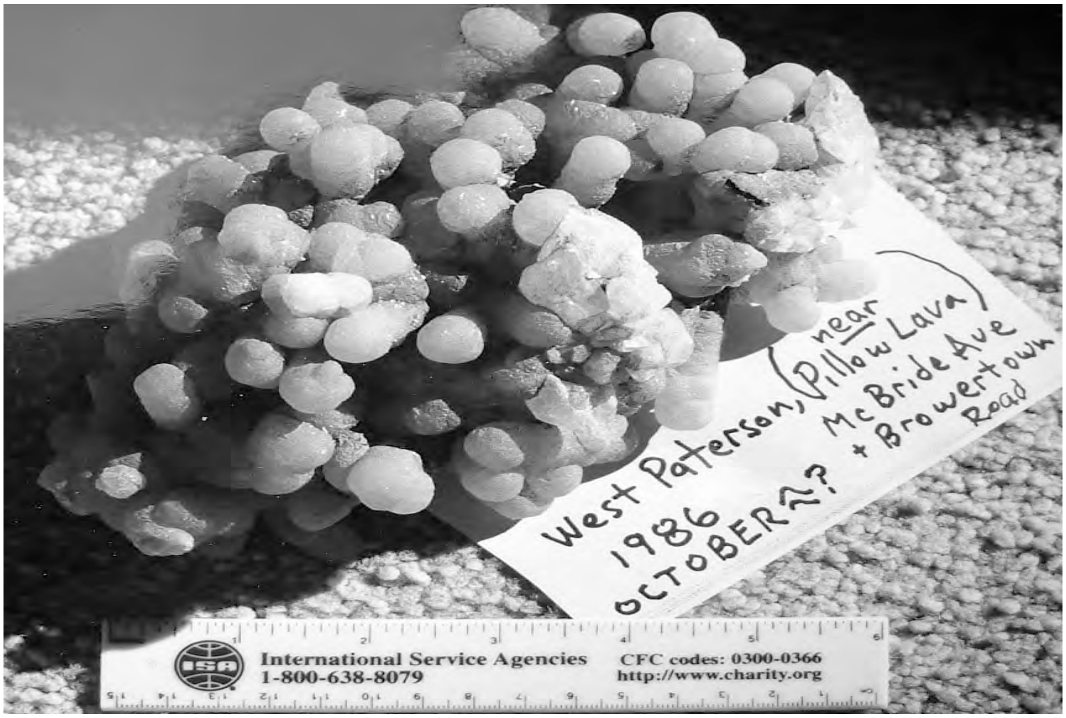

Figure 8. Prehnite from pillow lava at McBride Ave. and Browertown Road.

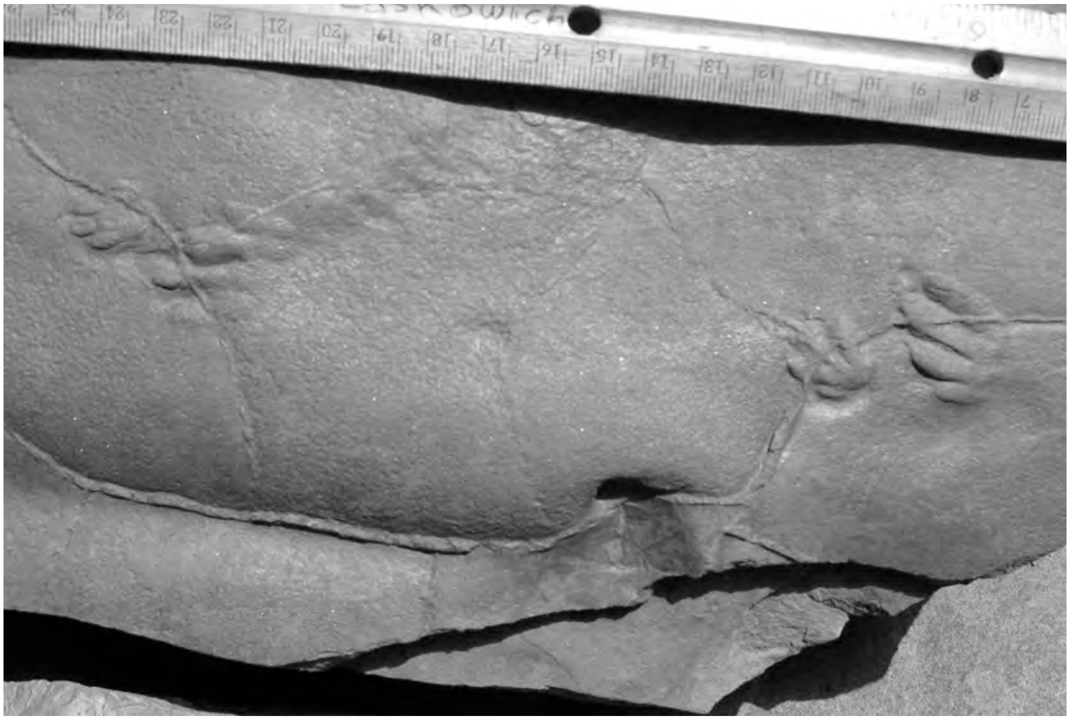

Figure 9. *Batrachopus* “crocodilomorph” foot and hand tracks from UBC quarry.

- Reptile tracks commonly found together with ripple marks and raindrop impressions – Reptile tracks with 4 toes, up to 2 inches long with claws and occasional scale prints are called *Batrachopus* and are attributed to crocodylomorphs (the group which includes the ancestors to today's crocodiles) (Figure 9). *Rhynchosauroides* tracks display slender, curved toes up to 2.4 cm long with tiny claws, followed by a single row of scales on smaller specimens; they are attributed to lepidosauromorphs (lizard-ancestors).
- Spirit River – A river course indicated by pillow lava, which only forms when lava is chilled to hardness quickly by water. (Paleoflow indicated by pillow orientation was east to west in the Montclair State University quarry.)
- Spirit Lake – The sediments below the lava were deposited in a large lake on the basis of varved lake sediment structure.
- Stilbite - Orange-brown stilbite commonly forms ball shapes up to 4 cm in diameter and "bow tie" shapes on shallow water pillow lava at the Montclair/Houdaille quarry
- Strike-slip faults (Figure 10) described by Puffer and Student (1992).

Figure 10. Strike-slip fault exposed on the basalt quarry face, UBC quarry.

THE HISTORY OF GREAT NOTCH AND THE PATERSON AREA

- The Lenni Lenape Indians named the Clifton area Aquankanonk
- The Morris Canal
- Iron mining and railroads (Susquehanna, Erie-Lackawanna)

- The Rogers Locomotive works, Paterson
- The Holland submarine on display at the Paterson Museum
- The Colt repeating pistol, Paterson
- The silk and textile mills, and the power of the Great Falls to run and make hydroelectricity.
- The Little Falls quarries for sandstone used for "brownstone" building blocks.
- Edison's Iron Mine and Portland Cement mass production, Ogdensburg and West.
- The trap-rock quarries of Great Notch used for railroad beds and concrete aggregate for foundations, roads and asphalt.
- The use of black powder, dynamite, and improved mining technology at trap-rock quarries
- Garret Mountain reservation and Rifle Camp Road Park nature preserves. From the loss of fresh water oysters from the natural spring at Clove Road and Rt. 46 to the resurgence of deer, turkeys, eagles, and wood peckers
- The loss of honey bees, moths, and mosquitoes.

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THE PARADOX OF LARGE CARCHARHINOID-TYPE SHARK VERTEBRAE IN THE UPPER CRETACEOUS OF NEW JERSEY

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ABSTRACT

Carcharhiniform and lamniform sharks are thought to derive from a common ancestral galeomorph during the Middle Mesozoic. Isolated carcharhinoid-type vertebrae found in the upper Cretaceous of New Jersey preserve anatomical characteristics, namely solid centra, analogous to vertebrae found in Cenozoic and modern carcharhiniforms. Conservative estimates of size based on total body length-centrum radius or diameter regressions for fossil and modern carcharhiniforms and lamniforms indicates that some of these Upper Cretaceous sharks with carcharhinoid-type vertebrae may have achieved total lengths of five meters or more. Paradoxically, a rich fossil record of shark teeth from the Upper Cretaceous of New Jersey and elsewhere in North America lacks any firm evidence for large-bodied ancestral carcharhiniforms. Although large lamniforms have left an abundant tooth record in the New Jersey Upper Cretaceous, the North American carcharhiniform tooth record is one of small-bodied genera (e.g., *Galeorhinus*, *Palaeogaleus*) unlikely to have possessed such large carcharhinoid-type vertebrae. However, one extinct family of large Upper Cretaceous lamniform sharks, the Anacoracidae, contains species with both lamniform teeth and carcharhinoid-type vertebral morphology. In New Jersey, two well-known anacoracids, *Squalicorax kaupi* and *Squalicorax pristodontus* co-occur in the same stratigraphic horizons as the large, isolated carcharhinoid-type vertebrae and represent the most-likely species for the origin of these vertebrae. Extinction across the Cretaceous-Tertiary boundary of large lamniforms with carcharhinoid-type vertebrae may explain the absence of this shared anatomical characteristic during the Cenozoic.

Figure and Table Abbreviations: b.c.- basal cartilage; bd.c.- basidorsal cartilage; b.m.- birth mark; bv.c.- basiventral cartilage; c.l.- concentric lamella; e.l.- enameloid; h.a.- haemal arch; n.a.- neural arch; o.d.- osteodentine; o.r.- orthodentine; r.l.- radial lamella; TL - total body length; v.p.- vertebral pore; v.r.- vertebral rim.

INTRODUCTION

One of the key features in the evolution of neoselachians was the appearance of a full series of well-calcified vertebrae surrounding the notochord (Maisey, 1996). A strong, calcified vertebral column is first noted to occur in *Palaeospinax* from the lower Jurassic (Applegate, 1967; Maisey, 1977), and is well established at the ordinal level by the Late Jurassic (e.g., Kriwet and Klug, 2004). Calcified vertebrae strengthen the vertebral column and provide additional support for trunk muscles and fin structures. This strengthening is also thought to allow for finer control over the frequency and amplitude of lateral undulations of the body, faster swimming, and greater effectiveness of the modified jaw apparatus (Stahl, 1974; Radinsky, 1987). Carcharhiniform and lamniform sharks, which include the largest, most powerful, and most mobile modern and fossil neoselachians, eventually evolved and diversified from these Middle Mesozoic vertebral innovators (e.g., Cappetta, 1987; Cappetta et al., 1993; Musick et al., 2004).

Carcharhiniforms currently total approximately two hundred and sixteen species arrayed in forty-eight genera and eight families, and comprise the largest and most diverse group of living sharks (Cappetta, 1987; Kent, 1994; Allen, 2003). However, carcharhiniforms have a poor fossil record prior to the Miocene when the majority of modern families and genera from this order are first known to appear (Kent, 1994). In contrast, modern lamniforms consist of only fifteen species arrayed in thirteen genera and seven families (Allen, 2003). However, they are well-documented in the Lower Cretaceous and were most abundant during the Middle and Late Cretaceous (Cappetta, 1987; Welton and Farish, 1993; Kent, 1994; Kriwet and Benton, 2004). Lamniforms were substantially reduced during the K/T mass extinction and have remained at low diversity throughout the Cenozoic (Kriwet and Benton, 2004).

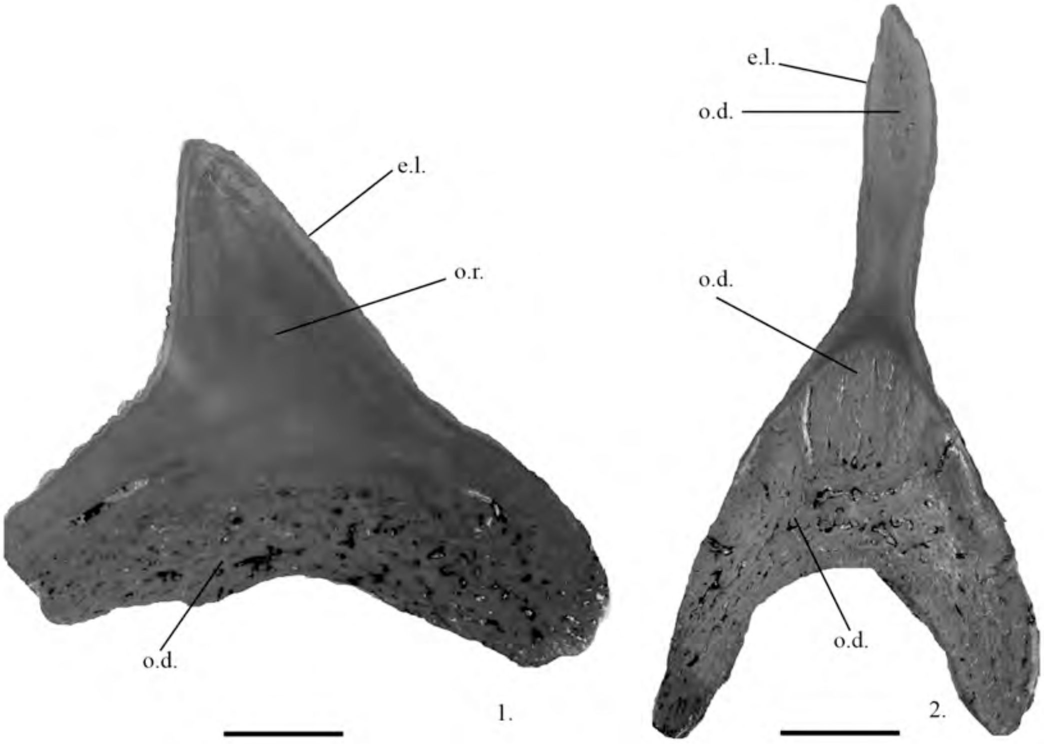

Figure 1. Tooth histology as seen in the (*1*) modern bull shark, *Carcharinus leucas*, carcharhiniform-orthodont and (*2*) modern mako shark, *Isurus oxyrinchus*, lamniform-osteodont. Scale bars =1.0 cm.

Carcharhiniform and lamniform physiological and anatomical characteristics support the idea of a close evolutionary relationship between the two groups, and suggest divergence from a common

Mesozoic ancestor (Musick et al., 2004). Both modern orders have a fusiform body, plesodic pectoral fins, segmented dorsal basals, anal fins, no fin spines, equivalent placement of the hyomandibula, and tripodal rostra internally supporting the snout (Cappetta, 1987; Springer and Gold, 1989; Allen, 2003). Distinctions between these two modern orders are subtle and based primarily on the nature of intestinal valves, differences in size and location of dorsal, pectoral, anal and caudal fins, presence of nictitating eyelids, and ability to thermoregulate. Unfortunately, such soft tissue characteristics have an exceedingly poor fossil record, as do partial or complete skeletons, and provide little resolution to systematic placement of isolated neoselachian skeletal remains. As such, researchers rely primarily on orthodont (carcharhiniform) or osteodont (lamniform) tooth histology as a means of identifying species and resolving classification issues in disarticulated neoselachian skeletal remains (Figure 1).

In New Jersey, isolated neoselachian vertebral centra are occasionally recovered in the same stratigraphic horizons as fossil carcharhiniform and lamniform teeth (e.g., Case, 1982; Becker et al., 2002). These fossil centra bear striking similarities to the centra of modern carcharhiniforms and lamniforms including amphicoelous morphology with double cone calcification, centrally located birth marks, concentric lamellae comprised of band pairs indicative of growth periodicities, and basidorsal and basiventral foramina for supporting neural and haemal arches. Such detailed anatomical characteristics suggest that similar ontogenetic processes of growth and skeletal development have been in operation throughout the evolutionary history of these neoselachians. If such an interpretation is correct, a comparison of fossil and modern carcharhiniform and lamniform vertebral centra should reveal some clues to the evolutionary history of spinal columns in these sharks.

CARCHARHINOID-TYPE AND LAMNOID-TYPE VERTEBRAE

Among modern carcharhiniform and lamniform sharks there are two main types of vertebrae. These are illustrated in Figures 2 and 3. Modern carcharhiniforms have vertebrae in which the centrum is composed of heavily calcified cartilage with no interior openings or gaps in the cartilage structure except for the spaces seating the basidorsal and basiventral cartilages that support the haemal and neural arches (Figures 2:1-3; 3:1-2). Modern lamniforms have vertebrae that contain prominent radial lamellae creating multiple partitions as well as openings for the basidorsal and basiventral cartilages that support the haemal and neural arches (Figure 2:4-6; 3:3-4).

Similar features to those seen in modern carcharhiniforms and lamniforms, particularly the presence or absence of radial lamella, can be observed in fossil centra from the Upper Cretaceous and Cenozoic (Figures 4-5). In fossil forms, observation of concentric lamellae and birth marks has been naturally enhanced through iron-enriched groundwater percolation and partial permineralization (Figures 4:1, 4:3, 4:5, 4:7, 4:9, 4:11). Additionally, neural and haemal arches are not preserved in the depicted fossil vertebrae due to the poor preservation potential of gelatinous cartilage that connects these features to the basidorsal and basiventral foramina in individual centra. (See neural and haemal arches in modern carcharhiniform and lamniform vertebral centra in Figures 2 and 3).

In this paper, we use the terms carcharhinoid-type and lamnoid-type to designate fossil Upper Cretaceous and Cenozoic vertebrae anatomically analogous to modern carcharhiniform and lamniform vertebrae respectively. In describing fossil vertebrae, use of term lamnoid-type can be found throughout fossil chondrichthyan literature (e.g., Applegate, 1967; Shimada, 1997a; b; Blanco-Piñón et al., 2005; and Shimada and Cicimurri, 2005) while use of the term carcharhinoid-type is less frequently encountered (e.g., Applegate, 1967). We note that the term scyliorhinoid-type vertebra has been previously used by various authors (e.g., Kent, 1994) for our carcharhinoid-type vertebra, but we refrain from its use due to the taxonomic connotations with Scyliorhinidae, the cat shark family. This family of small sharks, (typically less than one meter in total body length in modern species), has an exceedingly poor fossil record in the Upper Cretaceous of North America. Currently, there is no corroborating evidence from the Upper Cretaceous to indicate any scyliorhinids achieved large total body lengths or possessed the large vertebrae we describe here.

The Upper Cretaceous, Cenozoic, and modern carcharhinoid-type and lamnoid-type vertebrae analyzed in this study are reposited in the collections of: 1) Monmouth Amateur Paleontological Society (MAPS); 2) Philadelphia Academy of Natural Sciences (ANSP); 3) American Museum of Natural History (AMNH); 4) Sternberg Museum (FHSM); and, 5) William Paterson University (WPU). Literature sources used for vertebral terminology, identification, and comparison are: Applegate (1967); Compagno (1988); Welton and Farish (1993); Shimada (1997a; b); Blanco-Piñón et al. (2005); and Shimada and Cicimurri (2005).

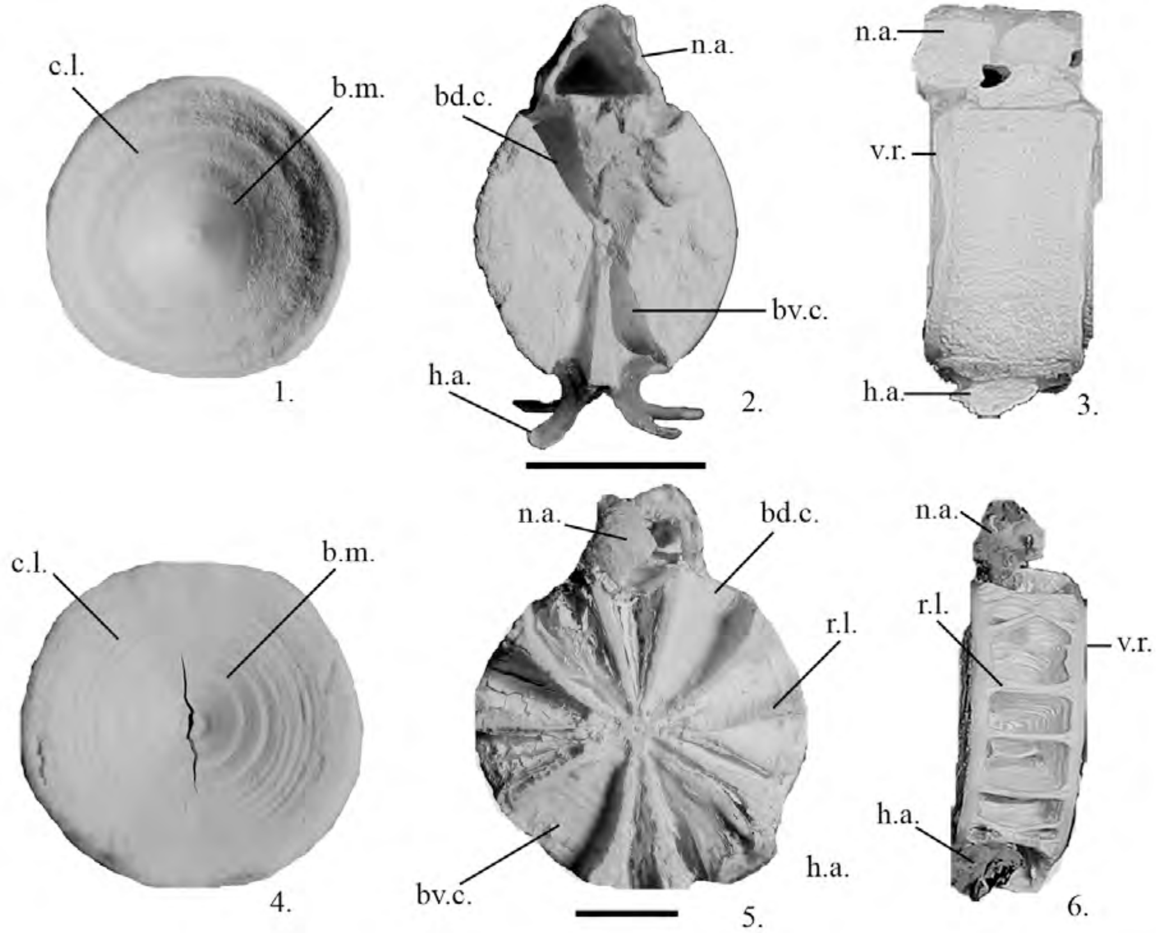

Figure 2. Modern carcharhiniform (*1-3*) and lamniform (*4-6*) vertebral centra. Articular surface view: *1*, *4*; Cross-section through articular surface: *2*, *5*; Dorso-lateral view: *3*, *6*. All scale lines equal 2 cm. *1-3*, Scalloped Hammerhead Shark, *Sphyrna lewini* AMNH 218209SD; *4-6*, Porbeagle Shark, *Lamna nasus* AMNH 96783SD.

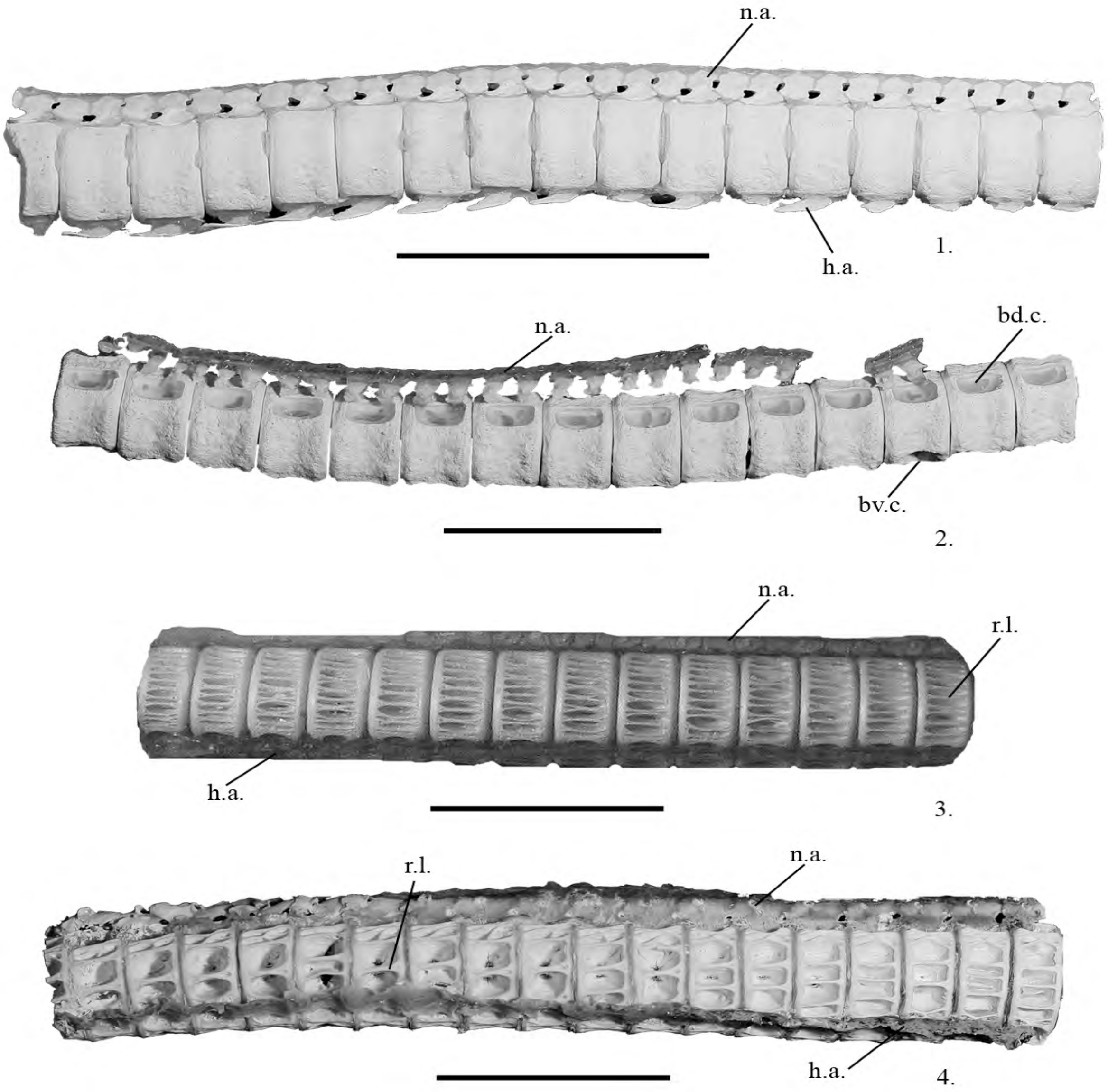

Figure 3. Articulated trunk sections in dorso-lateral view of vertebral columns from modern carcharhiniforms (*1-2*) and lamniforms (*3-4*). All scale lines equal 5 cm. *1*, Scalloped Hammerhead Shark, *Sphyrna lewini* AMNH 218209SD; *2*, Tiger Shark, *Galeocerdo cuvieri* AMNH 99059; *3*, Short-fin Mako Shark *Isurus oxyrinchus* WPU; *4*, Porbeagle Shark, *Lamna nasus* AMNH 96783SD.

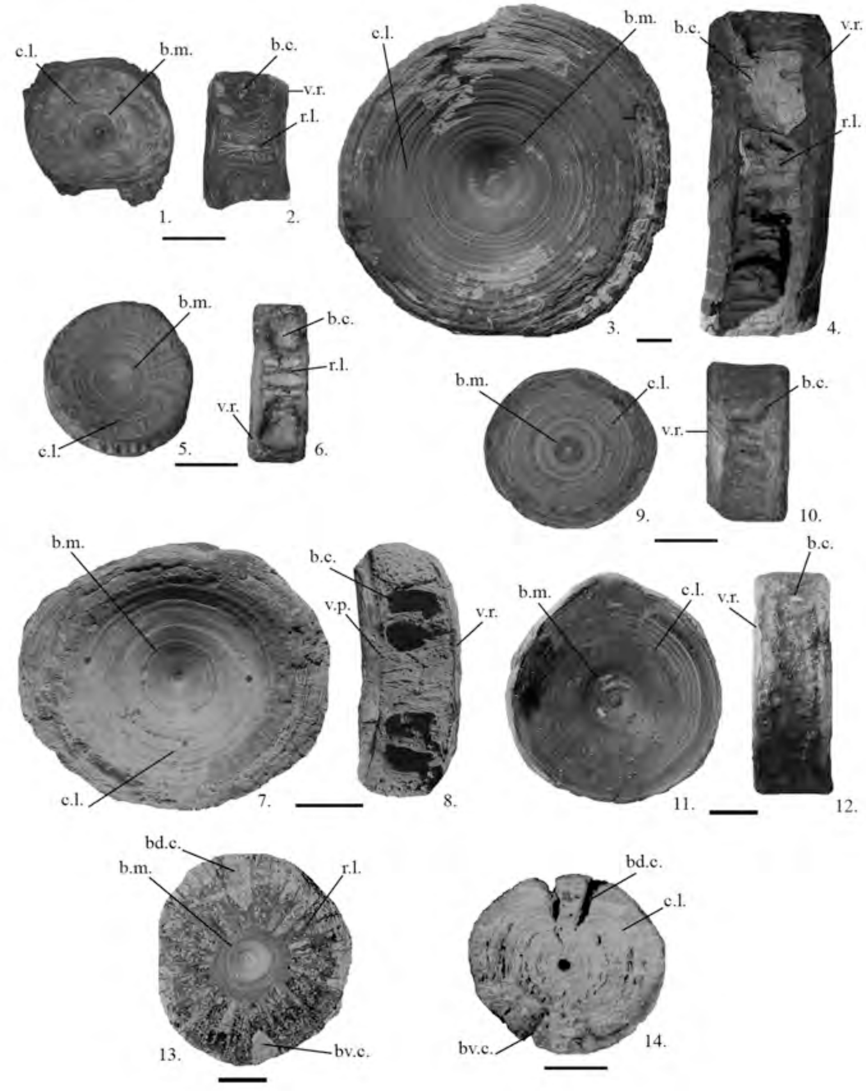

Figure 4. Lamnoid-type (*1-6*; *13*) and Carcharhinoid-type (*7-12*; *14*) vertebral centra from the Upper Cretaceous and Cenozoic of the Atlantic and Gulf Coastal Plains. Articular surface view: *1*, *3*, *5*, *7*, *9*, *11*. Dorso-lateral view: *2*, *4*, *6*, *8*, *10*, *12*. Cross-sectional view through articular surface: *13-14*. All scale lines equal 1 cm. *1-2*, Miocene, Bone Valley Formation, Polk Co, Florida; *3-4*, Eocene, Holmes Co., South Carolina, AMNH 3070; *5-6*, Upper Cretaceous, Taylor Group, Fannin Co., Texas; *7-8*, Late Hemphillian, Bone Valley Formation, Polk Co., Florida, AMNH unnumbered; *9-10*, Paleocene, Charles Co. Maryland; *11-12*, Late Campanian-early Maastrichtian, lowermost Navesink Formation, Monmouth Co., New Jersey; *13*, Santonian-Campanian, Tombigbee Sand Member, Greene Co., Alabama; (Note presence of radial lamellae); *14*, Campanian, Black Creek Formation, Bladen Co., North Carolina; (Note absence of radial lamellae).

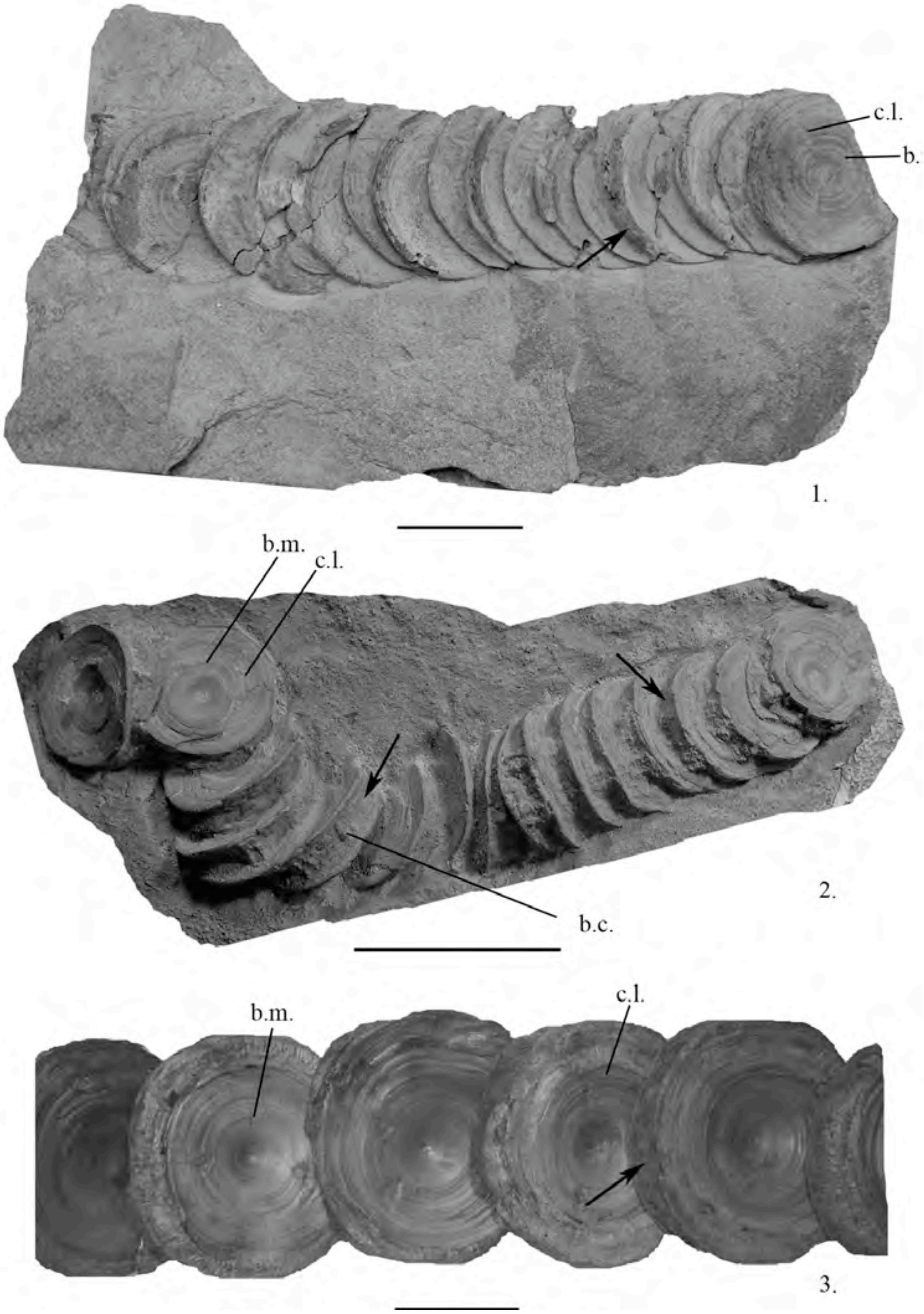

Figure 5. Carcharhinoid-type vertebral columns from Atlantic and Gulf Coastal Plains and Western Interior Seaway. All scale lines equal 5 cm. *1*, TXI Quarry, Eagle Ford Group (Cenomanian-Turonian) Midlothian, Texas (WPU); *2*, Niobrara Chalk, Grove Co., Kansas (*Squalicorax falcatus*; FHSM VP-190); *3*, New Egypt-Navesink Formations (Maastrichtian), Burlington Co., Arneytown, New Jersey (MAPS1026). Arrows point to solid centrum edges.

ANALYSIS AND CALCULATION OF TOTAL BODY LENGTH: METHODOLOGY AND DATA

Fifteen isolated, Upper Cretaceous carcharhinoid-type vertebrae, ranging in diameter from 38-71 millimeters, were selected for estimating the size of the animals from which they derive. Taken together, the collecting localities of these vertebrae span the entire inner coastal plain of New Jersey (Table 1). In order to estimate the unknown total body length from which the isolated carcharhinoid-type vertebrae derive, we used a combination of centrum diameter or radius to total body length formulas for fossil and modern carcharhiniforms and lamniforms from the references given in Table 1.

				Total Body Length of fossil sharks calculated from regression equations in references given in table legend. All Total Body Lengths in mm.					Average body length in mm.
Specimen	VD (mm)	NJ Locality	Catalogue#	Ref. 1	Ref. 2	Ref. 3	Ref. 4	Ref. 5	
1	71	A	MAPS	334.4	534.9	540.3	597.2	676.8	536.7
2	57	A	MAPS	267.9	435.7	439.4	520.3	547.9	442.2
3	54	G	ANSP 15422	253.7	414.5	417.8	495.2	520.3	420.3
4	49	C	ANSP15416	230.0	379.0	381.7	453.5	474.2	383.7
5	48	A	MAPS	225.3	371.9	374.5	445.1	465.0	376.4
6	46	H	ANSP No#	215.8	357.7	360.1	428.4	446.6	361.7
7	46	I	WPU	215.8	357.7	360.1	428.4	446.6	361.7
8	44	A	MAPS	206.3	343.6	345.7	411.7	428.2	347.1
9	43	C	ANSP No#	201.5	336.5	338.5	403.4	419.0	339.8
10	42	H	ANSP No#	196.8	329.4	331.3	403.4	409.8	334.1
11	42	D	MAPS	196.8	329.4	331.3	403.4	409.8	334.1
12	42	A	MAPS	196.8	329.4	331.3	403.4	409.8	334.1
13	42	E	MAPS	196.8	329.4	331.3	403.4	409.8	334.1
14	39	A	MAPS	182.5	308.1	309.6	370.0	382.2	310.5
15	38	A	MAPS	177.8	301.0	302.4	361.6	373.0	303.2

Table 1. New Jersey Upper Cretaceous carcharhinoid-type vertebrae selected for estimation of total body length. Formation and Location: A, Navesink Formation, Atlantic Highlands; B, Mt. Laurel and Wenonah Formations, Marlboro, Ramanessin and Big Brooks; C, Monmouth County; D, Wenonah Formation, Holmdel; E, Wenonah Formation, Marlboro; F, Navesink Formation, Marlboro, Big Brook; G, Mullica Hill; H, Sewell; Navesink Formation, Marlboro. (All available repository information for individual vertebrae specimens is provided). References for Total Body Length calculations: Reference 1 - Shimada and Cicimurri (2005) for *Squalicorax* (See Figure 6); Reference 2 - Cailliet et al. (1983) for modern short-fin mako shark, *Isurus oxyrinchus*; Reference 3 - Cruz-Martinez, et al. (2004) for modern bull shark, *Carcharhinus leucas*; Reference 4 - Branstetter and Musick (1994) for modern sand tiger shark, *Odontaspis taurus*; Reference 5 - Stevens (1975) for modern blue shark, *Prionace glauca.* Average total body lengths based on the five values calculated from the regressions in the references indicated.

Calculation of the total body length from the isolated Upper Cretaceous carcharhinoid-type vertebra was based on the following assumptions: 1) It is not possible to determine where along the spinal column the isolated carcharhinoid-type vertebrae derive. Modern and fossil sharks have highly variable vertebral counts with the largest vertebrae located in the trunk region directly below the anterior portion of the first dorsal fin (e.g., Shimada, 1997b; c; Goldman, 2004). Our total body length estimates assume that the isolated New Jersey vertebra is the largest vertebra from a particular individual. The isolated carcharhinoid-type vertebra may not have been the largest vertebrae included in the spinal column of a particular individual. Therefore, any estimates of total body length based on the isolated carcharhinoid-type vertebra should be conservative. 2) Vertebral diameter has the same size to total body length relationships for both fossil and modern galeomorphs. This assumes body form is relatively uniform among groups of sharks that possess carcharhinoid-type and lamnoid-type vertebrae. Rare fossil preservation instances of whole and partial skeletons support this uniformity (e.g., Shimada, 1997c; Kriwet and Klug, 2004; Shimada and Cicimurri, 2005). A similar set of assumptions were utilized by Shimada (1997b) in the determination of the total body length of isolated lamnoid-type vertebra from the Niobrara Chalk of Kansas.

Calculation of the total body length for the fifteen carcharhinoid-type vertebrae based on fossil lamniforms and modern carcharhiniforms and lamniforms can be seen in Table 1. The largest total body lengths were obtained by utilizing a modern blue shark, *Prionace glauca*, formula from Stevens (1975) with the largest individual well over six meters (Table 1; Ref. 5). The smallest total body lengths were achieved utilizing a derived formula based on *Squalicorax* (Figure 6) with the smallest individual just over one and three quarter meters (Table 1; Ref. 1). An average total body length determined by utilizing all five centrum diameters or radii to total body length formulas indicate the largest shark possessing carcharhinoid-type vertebrae measured just under five and a half meters and the smallest shark just over three meters.

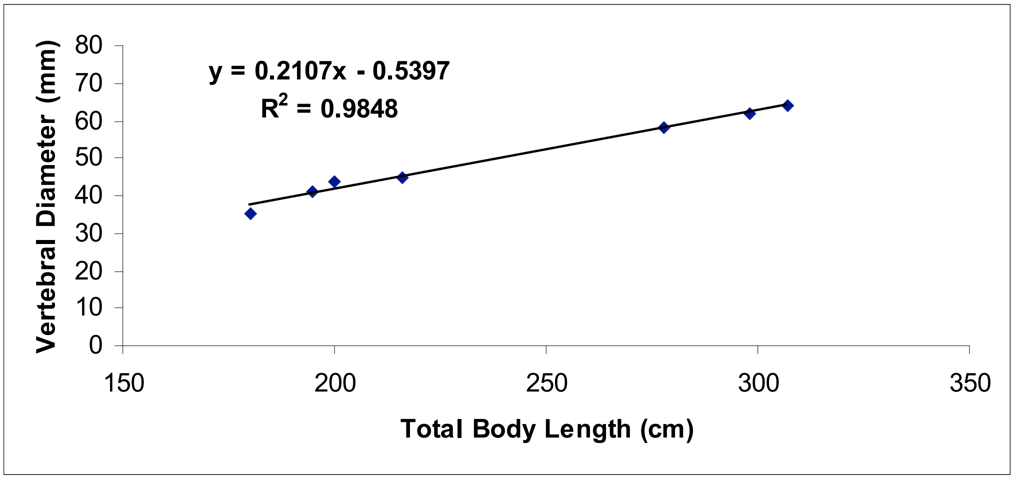

Figure 6. Linear regression for total body length versus vertebral diameter for the largest vertebra seen in partial or complete skeletons of the well-known and widely distributed upper Cretaceous lamniform *Squalicorax.* Raw data from Shimada and Cicimurri (2005). Each point represents one specimen.

DISCUSSION

The paradox of large isolated carcharhinoid-type vertebra: Body Size and Identity

In North America, many neoselachian fossils are preserved as isolated teeth, fin spines, vertebrae and dermal denticles in unconsolidated sediments that are the products of episodic sea level cyclicity and complex taphonomic histories (e.g., Case and Schwimmer, 1988; Robb, 1989; Becker et al. 1996, 1998, 2005, 2006). Under such taphonomic conditions, multiple complications can arise in interpreting the identity of disarticulated neoselachian fossils and the isolated New Jersey carcharhinoid-type vertebrae we report here are no exception. Comparison of the isolated New Jersey carcharhinoid-type vertebrae to articulated fossil and modern skeletons suggests large galeomorph sharks with carcharhinoid-type vertebrae existed during the Upper Cretaceous. However, the Upper Cretaceous chondrichthyan fossil record in North America has yet to provide a definitive example of a large galeomorph with orthodont teeth associated with carcharhinoid-type vertebrae.

In our analysis of carcharhinoid-type vertebrae, the largest total body length values were calculated by comparison to the modern blue shark, *Prionace glauca*. This is not surprising considering the fact that modern blue sharks are one of the more elongated and fusiform galeomorphs. This species of carcharhiniform lacks the broad-bodied trunk region seen in most modern carcharhiniforms and lamniforms such as the short-fin mako shark, *Isurus oxyrinchus* or bull shark, *Carcharhinus leucas*. Conversely, the smallest total body lengths were calculated from our derived formula based on partial and complete skeletons from Upper Cretaceous lamniforms. We attribute these smaller lengths to the limited number of available Upper Cretaceous individuals (seven specimens) where total body length data are available (Figure 6). However, regardless of such smaller total body lengths, all average total body lengths calculated for the fifteen New Jersey Upper Cretaceous carcharhinoid-type vertebrae by comparison to any modern galeomorphs would be considered large individuals.

By comparison to modern sharks, it is highly unlikely that the carcharhinoid-type vertebrae depicted in Figures 4-5 or utilized for total body length determination (Table 1) belonged to members from the heterodontiforms or orectolobiforms. The majority of modern sharks from both these orders, with two notable exceptions, the Ginglymostomatidae and Rhincondontidae, rarely exceed 100 cm in body size (Musick et al., 2004). However, neither of these two families represents a likely candidate for the isolated New Jersey carcharhinoid-type vertebrae. Fossil vertebral centra from Ginglymostomatidae are dorso-ventrally compressed with unequal ovoid faces that reflect animals evolved for a benthic life mode (Case, 1982; Robb, 1989; Kent, 1994; Becker et al., 2002). According to Applegate (1967) morphology in these centra has remained unchanged since the Jurassic. Additionally, genera from the Rhincondontidae are unknown until the Eocene (Welton and Farish, 1993; Kent, 1994; Müller, 1999).

Fossils from Upper Cretaceous carcharhiniforms such as scyliorhinids and triakids also prove to be problematic analogies for large carcharhinoid-type vertebrae. Modern scyliorhinids and triakids are small sharks, none of which exceeds 150 cm in body length (e.g., Musick et al., 2004), and comparison of their modern teeth to Upper Cretaceous fossil forms suggests such size proportions have remained constant (Figure 7). Fossils from the larger carcharhiniforms including the Sphyrnidae, Hemigaleidae, and Carcharhinidae do not appear until well into the Cenozoic (e.g., Müller, 1999; Kent, 1994; Tessman and Wing, 2001). The implication of these dichotomies is clear: either there were large Upper Cretaceous carcharhiniforms for which there is no known record, or some non-carcharhiniform Upper Cretaceous galeomorphs had vertebral morphology similar to that of fossil and modern carcharhiniforms. Considering the extensive literature on Upper Cretaceous fossil formations yielding large galeomorph teeth, an undiscovered large-toothed carcharhiniform is unlikely.

Partial and complete skeletons from the Cretoxyrhinidae including *Cretoxyrhina mantelli* demonstrate that at least some lamniforms possessed lamnoid-type vertebral centra. Previous research

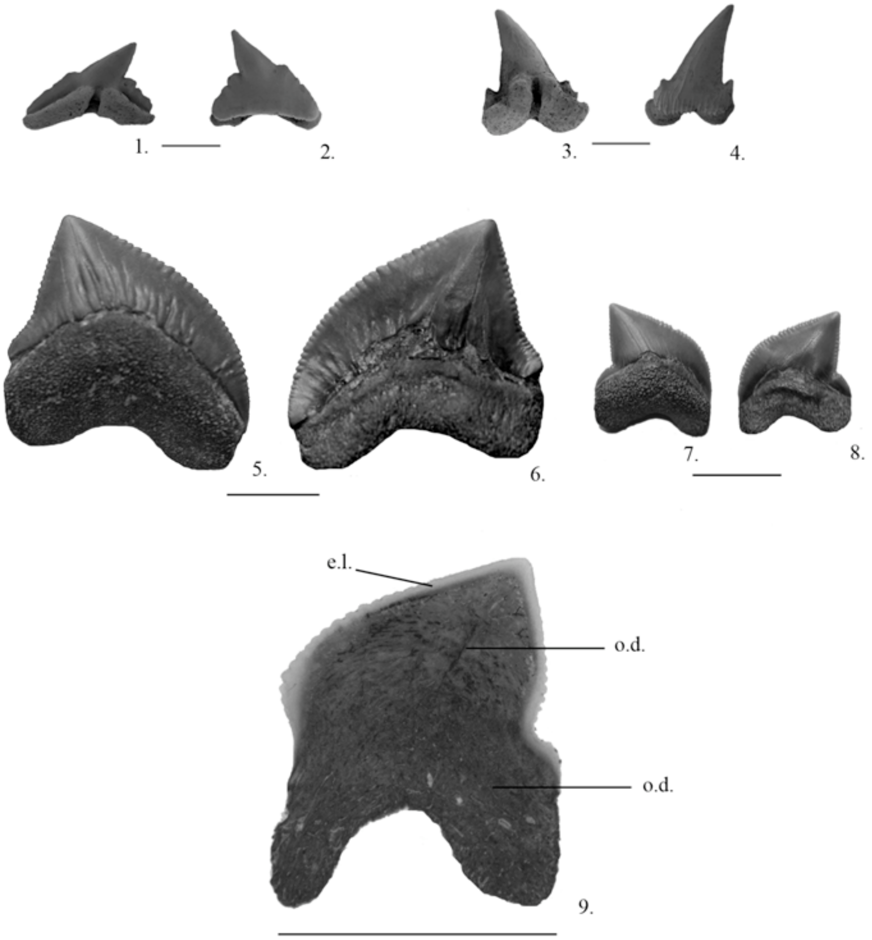

FIGURE 7. Examples of common Upper Cretaceous carcharhiniform (*1-4*) and lamniform (*5-9*) teeth from North America. *1-2*, *Galeorhinus girardoti*, Arkadelphia Formation (Maastrichtian) Hot Spring County, Arkansas; *3-4*, *Palaeogaleus* sp., Fairpoint Member of the Fox Hills Formation (Maastrichtian), Meade County, South Dakota; *5-6*, *Squalicorax pristodontus*, lowermost Navesink Formation (Campanian-Maastrichtian), Monmouth County, New Jersey; *7-8*, *Squalicorax kaupi* lowermost Navesink Formation (Campanian-Maastrichtian), Monmouth County, New Jersey; *9*, Thin section of *Squalicorax kaupi* demonstrating osteodont tooth tissues and lamniform affinities, lowermost Navesink Formation (Campanian-Maastrichtian), Monmouth County, New Jersey. Scale bars for figures *1-4* =1.0 mm; *5-9* =1.0 cm. All specimens are included in collections of WPU.

has also suggested that large lamnoid-type vertebrae may also occur in other members of the family Cretoxyrhinidae, such as *Cretolamna appendiculata* and *Leptostyrax macrorhiza* (Shimada, 1997b; Blanco-Piñón et al., 2005), although partial or complete skeletons associating these vertebrae and teeth have yet to be discovered. Although fossil evidence is limited, none of these species belonging to the Cretoxyrhinidae provides a likely association for the New Jersey carcharhinoid-type vertebrae. *Cretoxyrhina mantelli* and *Leptostyrax macrorhiza* have restricted chronological ranges and remain unknown in the late Upper Cretaceous formations from which our isolated carcharhinoid-type vertebrae derive. Although *Cretolamna appendiculata* occurs in the Upper Cretaceous of New Jersey, Applegate and Espinosa-Arrubarrena (1996) suggest this shark to be a possible ancestor of the well-known fossil lamniform *Carcharodon*. Fossil vertebral columns and skeletal evidence of *Carcharodon* clearly demonstrate this lamniform possessed lamnoid-type vertebrae (Applegate and Espinosa-Arrubarrena, 1996). This is true also of the modern white shark, *Carcharodon carcharias*.

We believe that the presence of large carcharhinoid-type vertebrae in the New Jersey Upper Cretaceous suggest that at least some lamniforms may have had vertebral columns similar to those of the early carcharhiniforms. This interpretation is supported by the fact that vertebral centra from partial and complete skeletons of *Squalicorax* have solid rimmed vertebrae with few radial lamellae supporting the primary double cone calcification (Shimada and Cicimurri, 2005; Figure 5-2). While the taxonomic placement of *Squalicorax* has been discussed by a number of chondrichthyan researchers, it is clear from its osteodont tooth histology that this Upper Cretaceous shark belongs with the lamniforms (Figure 7-9). (For a detailed review of the systematic placement of *Squalicorax* see Shimada and Cicimurri, 2005).

The anacoracid *Squalicorax* is well-known and abundant in North America from the Cenomanian through the Maastrichtian (e.g., Cappetta and Case, 1975; Case, 1978, 1987; Case and Cappetta, 1997; Case and Schwimmer, 1988; Robb, 1989; Manning and Dockery, 1992; Welton and Farish, 1993; Kent, 1994; Schwimmer et al., 1997; Hartstein et al. 1999; Becker et al., 1998, 2006). The fact that *Squalicorax kaupi* and *Squalicorax pristodontus* teeth (e.g., Cappetta and Case, 1975; Gallagher et al., 1986; Gallagher, 1993; Becker et al., 1996; Figure 7:5-9) can be recovered from the exact same formations as the isolated New Jersey carcharhinoid-type vertebral centra we describe here further reinforces our interpretation.

Is Squalicorax the producer of the large isolated carcharhinoid-type vertebra?

Three lines of evidence suggest an affirmative answer to this question: 1) the fact that *Squalicorax* has solid rimmed vertebrae with few radial lamellae supporting the primary double cone calcification (e.g., Figure 5-2); 2) the relationship between total body length and vertebral size in these Upper Cretaceous sharks; and 3) the relationship between tooth size and total body length in sharks generally. Figure 6 shows that vertebral size scales linearly with total body length in *Squalicorax*. The regression elucidated in Figure 6 is based on data reported by Shimada and Cicimurri (2005) on vertebral diameter in fossil *Squalicorax* specimens having complete or nearly complete vertebral columns. Figure 6 also indicates that most vertebrae of the size given in Table 1 should derive from animals with total body lengths of two to four meters which is well within the known size range of *Squalicorax*.

The relationship between total body length and tooth size in some fossil and modern sharks has been demonstrated to be species specific (e.g., Gottfried et al., 1996; Hamm and Shimada, 2002; Shimada, 1997d, 2003, 2005, 2006a, b; Shimada and Cicimurri, 2005). Analysis of Meckel's and palatoquadrate jaw cartilages with included teeth indicate individuals of *Squalicorax kaupi* were smaller than *Squalicorax pristodontus* (Shimada and Cicimurri, 2005). In their study, individuals from both these species were estimated to achieve lengths of three meters with the largest specimen of a probable *Squalicorax pristodontus* estimated at almost five meters. This relationship is also demonstrated in a comparison of maximum tooth size (from tooth root to crown apex) for *Squalicorax pristodontus* (29 mm) and *Squalicorax kaupi* (19 mm) by Welton and Farish (1993). Based on these analogies, the examples of *Squalicorax pristodontus* (28 mm) and *Squalicorax kaupi* (16mm) teeth depicted in figure 7:5-8, which co-occur with our carcharhinoid-type vertebrae, would represent large sharks. Such sharks would support our calculated average total body lengths (Table 1) that ranged from approximately three to five and a half meters and would be of equivalent total body lengths to those seen in partial and complete skeletons of the anacoracid *Squalicorax*.

There is one aspect of this analysis that leads to an interesting possibility. By applying the *Squalicorax* regression formula seen in Figure 6 to unusually large specimens such as Figure 5-3 (MAPS

1026) demonstrates that the animal for which these vertebrae derive had a total body length well in excess of three meters. We attribute such vertebrae to very large individuals of *Squalicorax pristodontus* that inhabited the waters of the New Jersey Coastal Plain during the Upper Cretaceous.

CONCLUSIONS

Although little information exists about morphological variation in vertebrae from extinct sharks, it is clear from the examples we describe here that large sharks with carcharhinoid-type vertebral morphology roamed the shallow seas of the New Jersey Coastal Plain during the Upper Cretaceous. The absence of radial lamellae in these isolated carcharhinoid-type vertebrae is anatomically analogous to vertebrae seen in carcharhiniforms throughout the Cenozoic. Paradoxically, no fossils, particularly of teeth, from a large Upper Cretaceous carcharhiniform, have yet been recovered from New Jersey or elsewhere in North America. Rare preservation examples of partial and complete skeletons from the Niobrara Chalk of western Kansas with associated teeth indicate at least one Upper Cretaceous family of sharks, the Anacoracidae, possessed carcharhinoid-type vertebrae. However, an osteodont tooth histology best associates this family of extinct sharks with the lamniforms.

Two members from the Anacoracidae, *Squalicorax kaupi* and *Squalicorax pristodontus* are common in the Upper Cretaceous of New Jersey. Moreover, teeth from both *Squalicorax kaupi* and *Squalicorax pristodontus* occur in the same geologic formations as the carcharhinoid-type vertebrae from this study. In the absence of fossil evidence from other galeomorphs, we believe the most-likely association for the carcharhinoid-type vertebrae from the Upper Cretaceous of New Jersey is the lamniform *Squalicorax*.

Current data based on species diversity in New Jersey and other North American localities indicate a substantial reduction in large, pelagic lamniforms across the K/T boundary. Although the exact driving mechanism of this end-Cretaceous extinction in marine ecosystems is still a matter of much debate, lamniforms that had carcharhinoid-type vertebrae were eliminated. The overall diversity in lamniforms has yet to fully recover.

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TEACHERS WORKSHOPS

TEACHING FORENSIC GEOLOGY

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DESCRIPTION

In the United States one can ascribe the start of the subfield of Forensic Geology to the 1975 textbook by Murray and Tedrow. However, at this time the field was not generally recognized by the geological community and was populated by individual practitioners. A notable exception to this was a course on Forensic Geology offered for a number of years by Jack Crelling at Southern Illinois University. Perhaps because of the recent popularity of the CSI TV shows and the mystery stories written by Sarah Andrews (which feature a heroin who is a forensic geologist), Forensic Geology has become recognized as an important activity within the geosciences. This is evidenced by forensic geology sessions at recent NE GSA and national GSA meetings. At this year's national GSA meeting there will be a public forum on geology and its use in criminal and civil investigations. In the United Kingdom, the Geological Society of London has established a working group on forensic geology.

Forensic Geology provides wonderful teaching opportunities, both as an integrative course for geoscience majors and as an introductory course for non-geoscience students. At the University of Massachusetts Lowell we offer an undergraduate studio-type course for Honors students (but also taken by students who are not Honors students). The course has attracted students from a number of disciplines – Biology, Chemistry, Physics, Computer Science, Psychology, Criminal Justice, and Management. The course is largely, but not completely, case-based. Students have to develop evidence for a criminal or civil case using geological principles. The approach is to first present the case, then determine what geological information might be useful, and then develop the techniques and knowledge needed to obtain this geological information. Many of the necessary concepts would be found in a traditional physical/historical geology course, but in this instance the motivation is different.

The workshop will present several case studies and the techniques needed to develop evidence for criminal and civil cases. Teachers will be provided with classroom materials, handouts, and PowerPoint presentations so that they can conduct their own classroom investigations.

TOPICS COVERED

1. Introduction to crime scene investigation
2. Determining the location of a crime scene using size and mineralogy of sand
3. Using rocks and geologic maps in forensic investigations
4. Contamination of groundwater supplies
5. The use of X-ray diffraction in criminal investigations

THE PROPOSED FOSSIL DISCOVERY CENTER AND THE STERLING HILL MINING MUSEUM EDUCATIONAL PROGRAMS: PAST, CURRENT AND FUTURE

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ABSTRACT

Since 1989 the Sterling Hill Mining Museum (SHMM) has been involved with various education programs for both students and teachers with regard to geology, mining and the history of New Jersey. The most fundamental educational program is a guided tour of the mine and exhibit halls as part of a school trip for grades 3 through 12. These tours are also opened to the general public and college students. The unique mineralogy and ore body at SHMM not only inspires teachers in their teaching experience, but awakens curiosity in students about the Earth, rocks and minerals, science and natural resources.

Since 1996 an option for schoolchildren is to participate in a geologic field experience through the Rock Discovery Center (RDC). Students are introduced to geology by collecting and identifying six rock and mineral specimens (basalt, garnet, marble, slate, coal and sandstone). These specimens represent the three major rock groups and indicate regional economic importance from having been quarried in the northeastern United States. It also empowers teachers with having hands-on materials for each student when returning to the classroom.

SHMM is in the preliminary stages of establishing a Fossil Discovery Center (FDC) similar to its successful RDC. Initial plans are for six specimens to be collected from a possible ten different types of fossils (fern fossil, petrified wood, 2 types of snails, 2 types of lamp shells, a crinoid stem, and 3 types of vertebrates). These different types of fossils will enable teachers to review various ways of preservation ("fossilization"), the diversity of life, geologic time, ecology, and evolution depending on the age group.

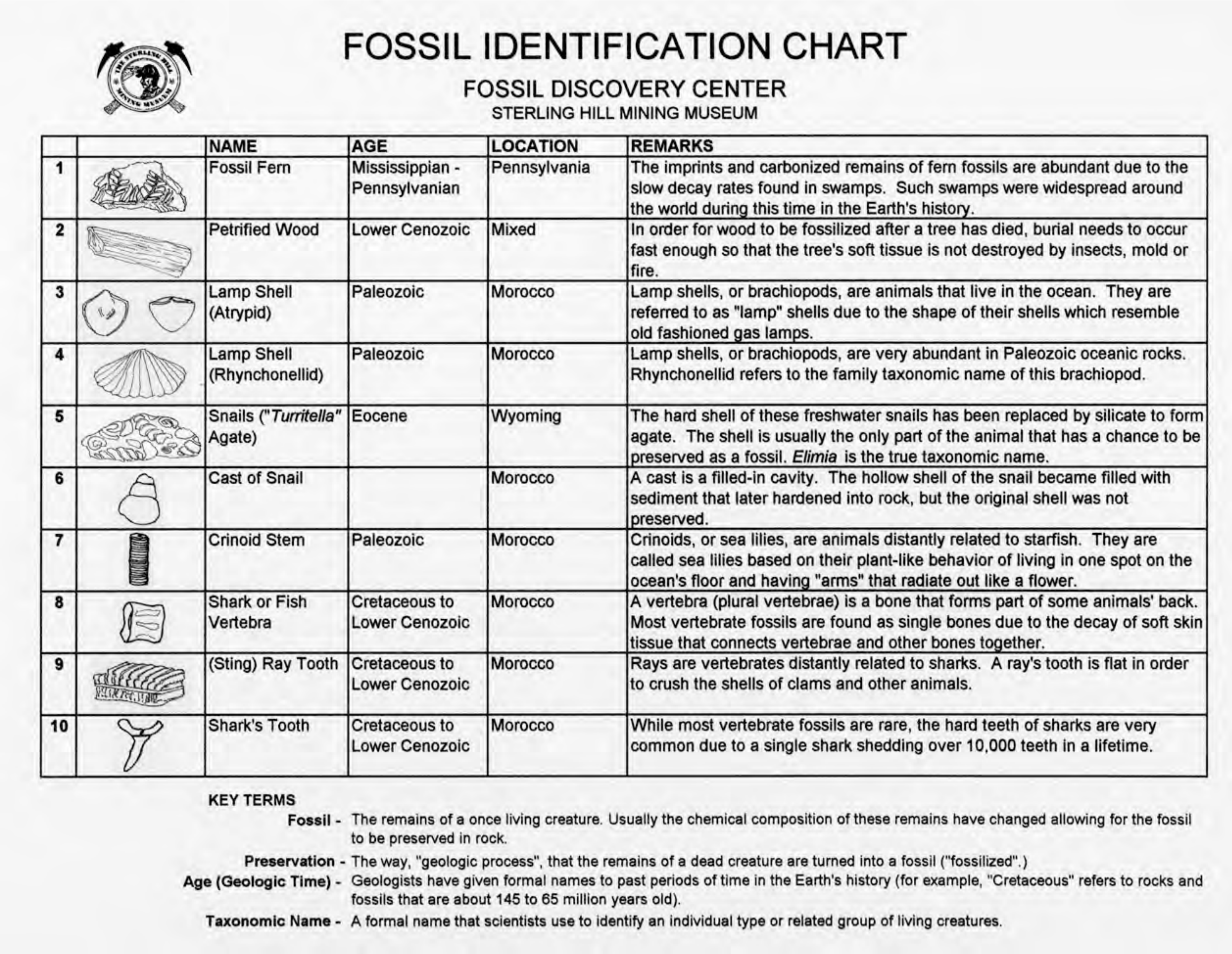
This (2007 GANJ) two-part Teacher's Workshop is a slide show emphasizing the various educational programs available at SHMM, and hands-on introduction to the proposed FDC. Teachers can use the FDC to meet various educational requirements (for example, 2004 NJ Core Standards 5.8.2D; 5.8.4A; 5.8.8C; 5.8.12C&D).

PROPOSED OUTLINE FOR THE FOSSIL DISCOVERY CENTER

The Sterling Hill Mining Museum is in the preliminary stages of establishing a Fossil Discovery Center similar to its successful Rock Discovery Center. Initial plans are for six specimens to be collected from a possible ten different types of fossils. These different types will enable teachers to review various ways of preservation ("fossilization"), the diversity of life, geologic time, ecology, and evolution, depending on the age group.

Purpose

The FDC would expand the currently successful RDC by allowing students to learn about paleontology and geologic time. It would also increase the number of educational opportunities at SHMM so that tours are less overcrowded.



FOSSIL IDENTIFICATION CHART

FOSSIL DISCOVERY CENTER

STERLING HILL MINING MUSEUM

		NAME	AGE	LOCATION	REMARKS
1		Fossil Fern	Mississippian - Pennsylvanian	Pennsylvania	The imprints and carbonized remains of fern fossils are abundant due to the slow decay rates found in swamps. Such swamps were widespread around the world during this time in the Earth's history.
2		Petrified Wood	Lower Cenozoic	Mixed	In order for wood to be fossilized after a tree has died, burial needs to occur fast enough so that the tree's soft tissue is not destroyed by insects, mold or fire.
3		Lamp Shell (Atrypid)	Paleozoic	Morocco	Lamp shells, or brachiopods, are animals that live in the ocean. They are referred to as "lamp" shells due to the shape of their shells which resemble old fashioned gas lamps.
4		Lamp Shell (Rhynchonellid)	Paleozoic	Morocco	Lamp shells, or brachiopods, are very abundant in Paleozoic oceanic rocks. Rhynchonellid refers to the family taxonomic name of this brachiopod.
5		Snails ("*Turritella*" Agate)	Eocene	Wyoming	The hard shell of these freshwater snails has been replaced by silicate to form agate. The shell is usually the only part of the animal that has a chance to be preserved as a fossil. *Elimia* is the true taxonomic name.
6		Cast of Snail		Morocco	A cast is a filled-in cavity. The hollow shell of the snail became filled with sediment that later hardened into rock, but the original shell was not preserved.
7		Crinoid Stem	Paleozoic	Morocco	Crinoids, or sea lilies, are animals distantly related to starfish. They are called sea lilies based on their plant-like behavior of living in one spot on the ocean's floor and having "arms" that radiate out like a flower.
8		Shark or Fish Vertebra	Cretaceous to Lower Cenozoic	Morocco	A vertebra (plural vertebrae) is a bone that forms part of some animals' back. Most vertebrate fossils are found as single bones due to the decay of soft skin tissue that connects vertebrae and other bones together.
9		(Sting) Ray Tooth	Cretaceous to Lower Cenozoic	Morocco	Rays are vertebrates distantly related to sharks. A ray's tooth is flat in order to crush the shells of clams and other animals.
10		Shark's Tooth	Cretaceous to Lower Cenozoic	Morocco	While most vertebrate fossils are rare, the hard teeth of sharks are very common due to a single shark shedding over 10,000 teeth in a lifetime.

KEY TERMS

Fossil -	The remains of a once living creature. Usually the chemical composition of these remains have changed allowing for the fossil to be preserved in rock.
Preservation -	The way, "geologic process", that the remains of a dead creature are turned into a fossil ("fossilized".)
Age (Geologic Time) -	Geologists have given formal names to past periods of time in the Earth's history (for example, "Cretaceous" refers to rocks and fossils that are about 145 to 65 million years old).
Taxonomic Name -	A formal name that scientists use to identify an individual type or related group of living creatures.

Layout

Unlike the RDC, specimens would be dug up by students rather than surface collected. Small plastic sieves would be used to screen out specimens from clean quartz sand. Initial plans are for six specimens to be collected from a possible ten different types of fossils (fern fossil, petrified wood, two types of snails, two types of lamp shells, a crinoid stem, and three types of vertebrates). The box for collected specimens will have a Fossil Identification Chart (Figure 1). The “Beginner’s” version of this chart includes a picture of the specimen, a general name, the geologic age, location, and remarks for each type of fossil. Iconic recognition is the emphasis of this version. Back in the classroom, the different types of fossils will enable teachers to review various ways of preservation (“fossilization”), the diversity of life, geologic time, ecology, and evolution, depending on the age group. Teachers can use the FDC to meet various educational requirements (for example, 2004 NJ Core Standards 5.8.2D; 5.8.4A; 5.8.8C; 5.8.12C&D).

FIELD GUIDE

ROAD LOG

Segment start (mi)	Directions/Notes
0.0	From Green St parking lot, proceed northwest on S. Green St.
0.3	Turn left (SW) on Analomink St.
0.5	Turn left (S) on Crystal St.
0.6	Turn right (W) on Washington St., which will bear left and become business route 209. Proceed over bridge.
1.4	Turn right (SW) on Sarah St.
1.5	Turn right (N) on N 5th St. / PA-191
1.7	Turn left (W) on Brown St. and proceed one block.
1.8	Turn left (S) on Wallace St. and park in gravel area on right.
	Travel time: approx. 10 minutes

Stop 1: Brown Street quarry, Stroudsburg (Paul S. Boyer, Fairleigh Dickinson University)

1.8	Turn left out of parking area and proceed north on Wallace St.
2.0	Turn right (E) on Phillips St. and proceed one block.
2.1	Turn left (N) on PA-191.
7.0	Outcrop of Mahantango Formation (Centerfield Biostrome). Park in Pinebrook Park and *carefully* cross over to the outcrop.
	Travel time: approx. 10 minutes

Stop 2: Centerfield Biostrome, Stroud Twp. (Paul S. Boyer, Fairleigh Dickinson University)

This site is on private property, permission must be obtained to visit it.
No collecting or hammering on the outcrop.

7.0	Continue north on PA-191.
7.4	Turn right (S) on PA-447 (Courtland St.).
9.4	At traffic light, turn left (N) on US-209 (business route).
12.8	Continue straight on US-209.
19.3	Entering Delaware Water Gap National Recreation Area – *no rock/fossil collecting within DWGNRA.*
27.5	Turn left (NW) on Brisco Mt. Road, following signs for PEEC.
28.4	Turn right (N) on Emery Road.
28.5	Turn in to PEEC.
	Travel time: approx. 30 minutes

Stop 3: Pocono Environmental Education Center (Emma C. Rainforth, Ramapo College)

This site is in DWGNRA; no collecting or hammering on the outcrop.

LUNCH

28.7	From PEEC, turn left (S) on Emery Rd.
28.8	Turn left (SE) on Brisco Mt. Rd.
29.7	Turn left (N) on US-209.
42.0	Turn right (S) on US-206 and cross Delaware River.
42.9	Bear left (N) on Sussex Co. Rt. 521
43.0	Turn right (N) on Rubin Hill Road.
43.6	Park in gravel area on right, just before stop sign.
	Travel time: approx. 30 minutes

Stop 4: Rubin Hill Road, Montague (Arlene Castleman, New Jersey Paleontological Society)

This site is on private property, permission must be obtained to visit it.

43.6	Continue north on Rubin Hill Rd and immediately turn right (S) on Clove Road (Sussex Co. Rt. 653).
43.9	Turn left (E) on Deckertown Tpk. (Sussex Co. Rt. 650).
44.3	Outcrop of Montague Reef in the woods on the left.
56.6	Turn right (S) on NJ-23.
57.5	Turn left at traffic light and right after one block to remain on NJ-23.
62.4	Turn right immediately before railroad bridge onto Gingerbread Castle Road.
62.8	Turn left into Ballyowen Bluffs estate. Park at top of hill.
	Travel time: approx. 30 minutes.

Stop 5: Gingerbread Castle Stromatolites, Hamburg, NJ (Deborah Freile, New Jersey City University)

This site is on private property, permission must be obtained to visit it.
No collecting or hammering on the outcrop.

63.0	Turn left out of Ballyowen Bluffs onto Gingerbread Castle Road.
64.5	Turn left (S) on NJ-94.
97.4	Merge onto I-80 westbound.
104.5	Take exit 308 and turn right (N) onto Prospect St.
104.9	Turn left (E) on Normal St.
105.0	Turn left (N) on Green St. and into parking lot.
	Travel time: approx. 75 minutes

STOP 1: MARCELLUS FORMATION AT OLD BROWN STREET QUARRY, STROUDSBURG, MONROE CO., PA

Paul S. Boyer
Department of Chemistry and Geology, Fairleigh Dickinson University, 285 Madison Ave., Madison, New Jersey 07940-1099

Collecting is permitted at this outcrop.

LOCATION

Stroudsburg 7.5-minute Quadrangle.
This former quarry is located about 400 m north from the Courthouse, just southwest of the intersection of Brown Street and Wallace Street (Figure 1).

Figure 1. Exposure of the Marcellus Formation at the old Brown Street Quarry

SITE DESCRIPTION

The Marcellus Formation (formerly called the Marcellus Slate, and later the Marcellus Shale) is a dark gray to black carbonaceous shale with well poorly developed cleavage. It spreads widely over New York and Pennsylvania, and is more uniform in its lithology than any other of the Devonian formations. It overlies conformably a sequence of calcareous units, from which it initiates a distinct transition to more terrigenous, and also carbonaceous sedimentation. This change marks the start of the Hamilton Group, widely known for its rich fossil content, particularly father to the west.

At this site, the Marcellus Formation is find-grain and arenaceous. Although the quarry reveals only at most 9 m, the formation reaches its greatest total thickness here in Monroe County (about 270 m. according to Willard, 1939, p. 169). Where covered by subsequent formations, as in the Appalachian Basin, the Marcellus Formation is a producer of natural gas, and a prospect for petroleum.

The portion of the Marcellus Formation exposed at this site has been named by Willard (1939, p. 171) the Brodhead Member.

PALEONTOLOGY

Most of the fossils to be found at this exposure are small. A hand-lens would help in spotting some of them. Although over the years a good variety of marine organisms has been found here, one generally finds only a few species during a short visit. The most abundant are the small brachiopods, particularly *Liorhynchus limitare* (Vanuxem), the most characteristic species of the Marcellus Shale (Prosser, 1905). Vanuxem noted that in New York State the species is restricted to the lower, shaley part of the Hamilton Group, and was most abundant near the upper boundary of the Marcellus Shales, "from whence its name" (Vanuxem, 1842, p. 147).

Also locally abundant at this quarry is a very small, discoidal bryozoan, only a few mm across, which somehow (as far as I know) has escaped further study, and does not appear to have been identified, other than being noted as "Bryozoan indet." (Willard, 1939, p. 171). Occasional pieces of the trilobite *Homalonotus* turn up: one must be alert for fragments, because no complete specimens have yet been found here. Figure 2 shows examples of species represented at this location.

ENVIRONMENT

It is assumed that the sea floor was stagnant (anoxic) during most of the deposition of the Marcellus Formation. A number of writers have cited this formation as a typical result of such environments, and state that they are characterized by small fossils of limited variety. There have even been comparisons with the conditions on the floor of the Black Sea, where seasonal or otherwise episodic times of overturn (perhaps brought on by storms) brings in enough oxygen to allow colonization by young shellfish larvae, only to have the hopeful colonists die off when the reigning euxinic conditions return.

As you look at the fossils here (or, at least, as you look *for* them!), perhaps you might consider another possibility: that most of the preserved animals here were not benthic (bottom-dwelling) at all. It is notable that there are very few creatures represented which could tolerate living in deoxygenated waters. Some bivalves might have tolerated such an environment, for some are very tolerant of low oxygen levels even today. There are, however, only rare pieces of one species of trilobite. Trilobites were predominantly deposit-feeders, crawling over and within muds, subsisting on the organic debris adsorbed on clay particles, much as earthworms do in a garden (Seilacher, 1959). Yet trilobites are very rare here. The commonest fossils here are members of the lophophorate phyla, which do not thrive in stagnant water. What are they doing here?

Observe that here the common fossils are small. I would suggest that most of what we see are *epiplanktic* organisms: those which lived attached to floating objects such as algae. They are for the most part small by necessity; for only small creatures can live by adhering to seaweed. Of course, maybe they were bottom-dwellers which simply washed in with storms, and were subsequently smothered. But look at that small bryozoan, and try to imagine such delicate colonies surviving so perfectly the mill of sedimentary transport. Much more likely would seem the possibility that those "Bryozoa indet." were attached to seaweed, and after death (perhaps when their algal substrate foundered) gently drifted to the bottom.

The possible causes for the environment which gave us the dark shales such as the Marcellus Formation has been thoroughly studied, as one might expect in view of it hydrocarbon content. Werne *et al*. (2002) envision tectonic and eustatic events which altered the sediment supply and changed circulation patterns to bring about the anoxic bottom waters of the Hamilton Group.

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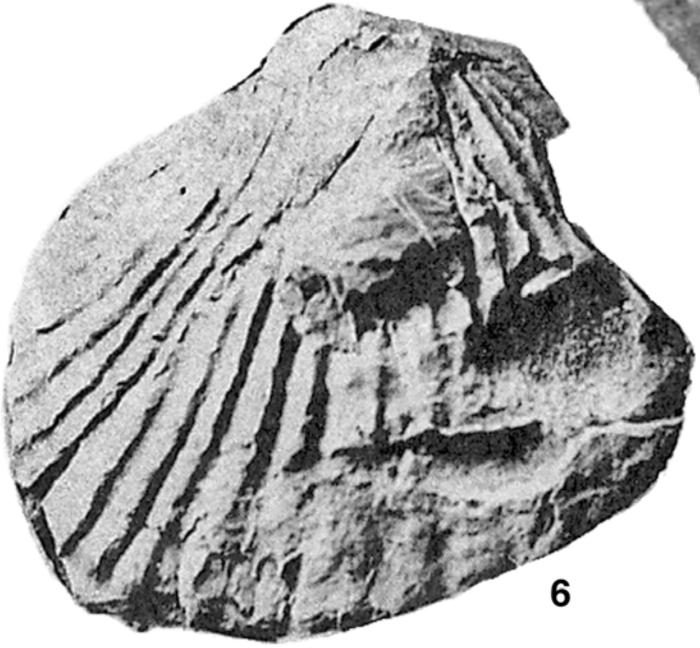

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Figure 2 (facing page). Fauna of the Marcellus Formation at the Brown Street Quarry. All x2 except as otherwise noted. BRACHIOPODA: 1. *Chonetes mucronatus* Hall. 2. *Liorhynchus limitare* (Vanuxem). 3. *Ambocoelia nana* Grabau. BIVALVIA: 4. *Aviculopecten invalidus* Hall. 5. *Nyassa arguta* Hall. 6. *Paneka costata* Hall. TRILOBITA: 7. *Trimerus dekayi* (Green), x 0.5. At the Brown Street Quarry, only fragments of this trilobite species have been found. *INSERTAE SEDIS*. 8. *Styliolina fissurella* (Hall), x 4
These figures are from Willard, 1939, and represent specimens from the Brown Street Quarry, with the exception of 7, which is from Hamilton Group in Madison Co., New York, and is in the New York State Museum (NYSM E958).

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STOP 2: CENTERFIELD BIOSTROME, STROUD TOWNSHIP, MONROE CO., PA

Paul S. Boyer
Department of Chemistry and Geology, Fairleigh Dickinson University, 285 Madison Ave.,
Madison, New Jersey 07940-1099

Collecting is limited to specimens in float only.
Leave hammers in the buses.

LOCATION

East Stroudsburg 7.5-minute Quadrangle.
This site is located on the west side of North 5th Street (Rt. 191), about 900 m south of the crossing of that road over Brodhead Creek (Figure 3).
This roadside outcrop is on private land; permission to visit must be obtained from Pinebrook Bible Conference and Retreat Center.

Visitors are warned to stay by the side of the road, for traffic coming around the curve at the north end of the exposure has very poor visibility.

Figure 3. Exposure of the Mahantango Formation and the included Centerfield Biostrome

Figure 4. The coral-rich layer of the Centerfield Biostrome as exposed in the south side of the eastbound lane of Interstate 80, near mile-marker 135. (The coin for scale is a quarter, 24 mm in diameter.)

SITE DESCRIPTION

This locality is one of the most renowned fossil sites in Pennsylvania. It was described and pictured by Willard (1939, pp. 177-178). Hoskins (1964, p. 87) used it to represent Monroe County in his guide.

Willard called the coral-rich exposure the “Centerfield coral zone” because he correlated it with the Centerfield Limestone of New York State. It has been called informally the Centerfield Reef, and the Centerfield Coral Reef, but Hoskins noted that it is not a true reef, because it is not a mound. It also does not appear to have been elevated above the surrounding sea floor, nor does it show evidence of resistance to waves, as required by the modern definition of a reef (Bates and Jackson, eds., 1987, page 555.) The deposit does conform to the definition of a **biostrome**, “a distinctively bedded and widely extensive or broadly lenticular, or blanketlike mass of rock built by and composed mainly of the remains of sedentary organisms, and not swelling into a moundlike or lenslike form; an ‘organic layer’, such as a bed of shells, crinoids, or corals, or a modern reef in the course of formation, or even a coal seam.” That definition is not without some difficulties: for example, lenticular means lenslike; and it is hard to understand why a modern reef in the course of formation can be called a biostrome, but not the finished product. Nonetheless, “biostrome” is probably preferable to “reef” in this case.

Unlike its correlatives in western New York, the rock here is not by any means a limestone. It is mostly terrigenous (“clastic”): a dark shale “replete with corals and other organisms, many of them reef-builders” (Willard, 1939, 178). The bedding is indistinct, but is made obvious by the crude layering of the skeletal debris. Where the exposure is near the land surface, downward percolation of acid waters has dissolved the carbonate (mostly calcite) from the fossils, so that molds are all that is left. In fresh road-cuts or other construction sites, it is possible to find shelly material intact.

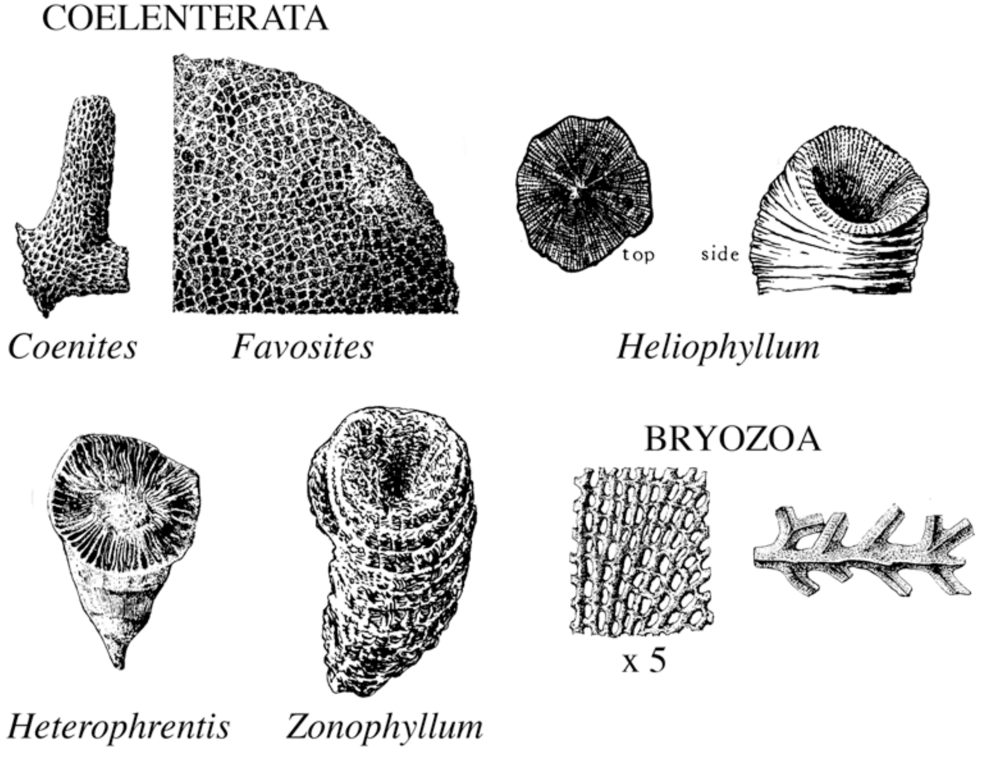

Figure 5. Coelenterata and Bryozoa of the Centerfield Biostrome. All x 1 except as noted. Drawings after Hoskins (1964).

PALEONTOLOGY

Willard (1939) gives a partial faunal list for this locality, but it is incomplete, and many of the names are not updated. Hoskins (1964) also gives a list, but only to genera. It is, nonetheless, a useful aid to identification. (His guide is out-of-print, and I recently have seen copies offered for sale on the Internet for from $79 to $450.) Reproduced here (Figures 5-7) are Hoskins' illustrations for the Centerfield fauna.

Ellison (1965) covers the Mahantango Formation in south-central Pennsylvania, far from our site. Nonetheless, his book (also unfortunately out-of-print) has numerous illustrations of fossils, some of which occur in Monroe County.

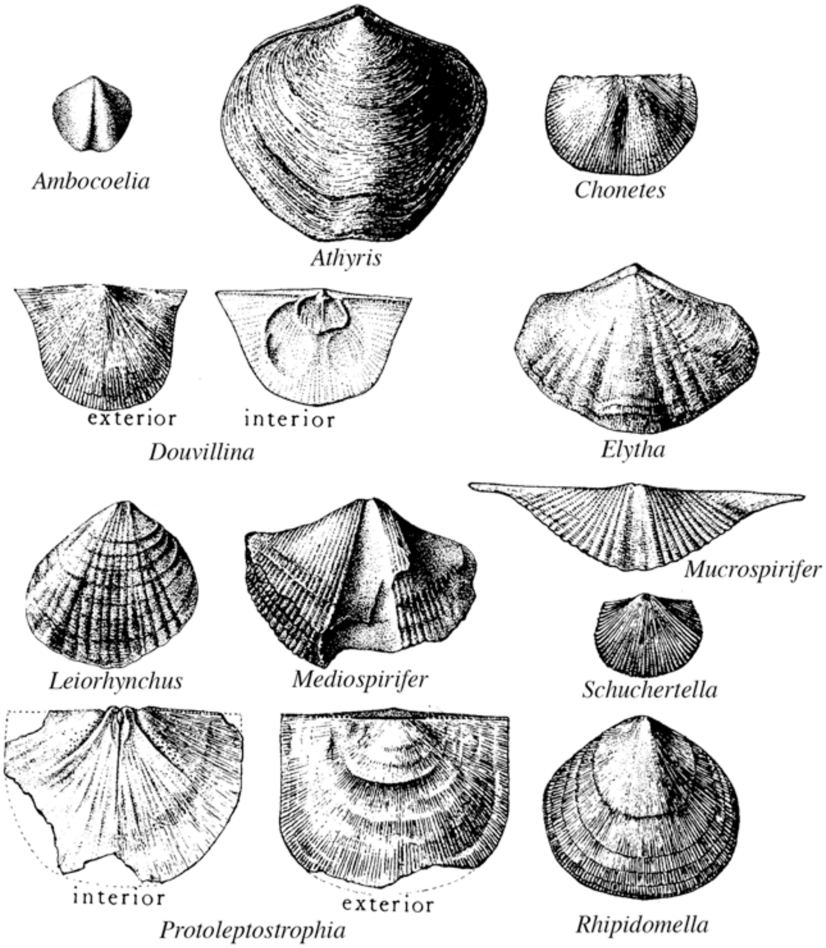

Figure 6. Brachiopoda of the Centerfield Biostrome. All x 1. Drawings after Hoskins (1964).

ENVIRONMENT

"The Centerfield Biostrome" represents a period of extreme abundance of coral growth. Apparently, though mud was being deposited here, the 'horn' corals could grow fast enough to keep from being totally buried in the mud. They grew with the small end downward. The water must have been relatively clear, however, for the brachiopods and other animals to live." Thus Hoskins (1964) summarizes what we might see as the main question about this deposit. How did so many sessile-benthic

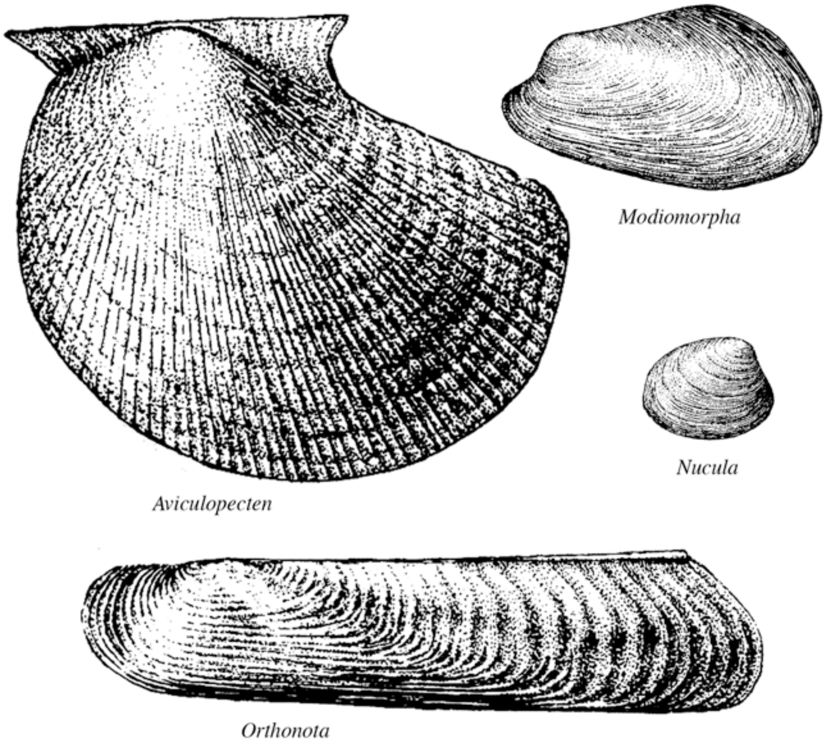

Figure 7. Bivalvia of the Centerfield Biostrome. All x 1. Drawings after Hoskins (1964).

Figure 8. The two phacopid trilobite species found in the Centerfield Biostrome: *Phacops rana* (left) and *Greenops boothi* (right). These particular specimens are not from Monroe County, but are shown here as aids for identification. (Pictures courtesy of Valdosta State University Virtual Fossil Museum)

organisms survive on a terrigenous, muddy sea floor, under conditions which were preserving so much carbonaceous material? There is little sign of winnowing which would give evidences of current activity.

It also appears that the skeletal debris show little or no evidence that they were actually growing and flourishing in the sedimentary environment in which we find them today. There is no sign of any hard grounds which would favor coral growth. There are no trilobite trails. The crinoid columnals are common, but never articulated. There is little order to the array of mixed debris. The corals themselves are virtually never found in growth position, and the branching forms are broken, and lying on their sides (as shown most clearly in the cuts on Interstate 80, which unfortunately we cannot visit).

It would seem that this deposit does not represent a flourishing area for benthic life, but is more like a graveyard of transported debris. If so, it is an extensive cemetery, for the Centerfield bed can be traced across several counties east of the Susquehanna River (Willard, 1939, p. 178). Correlative fauna continue westward in even richer abundance, as the carbonate content of the rock increases.

If the shelly debris was transported, where did it originate? How did it end up in sediments which imply an inhospitable environment for most of the represented organisms? Were storms or tsunamis involved, or some slumping mechanism?

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STOP 3: POCONO ENVIRONMENTAL EDUCATION CENTER, DINGMANS FERRY, PA

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This locality is within the Delaware Water Gap National Recreation Area.
Collecting is not permitted at this outcrop.
Leave hammers in the buses.

Participants may hike the Fossil Trail to the main fossiliferous outcrop. Lunch will be eaten at the Pavilion.

LOCATION

Lake Maskenozha, PA-NJ 7.5-minute Quadrangle.

INTRODUCTION

The PEEC is situated in the late Middle Devonian Mahantago Formation (upper Hamilton Group), which dips steeply westward in this area. The Fossil Trail (Figure 1) is marked by blue blazes, and leads to a fossiliferous outcrop (marker # 14). Fossils from this formation are on display in the PEEC visitor center as well as at the NPS visitor center at Dingman Falls.

PALEONTOLOGY

This site bears several brachiopod species, crinoid stems, and trilobite (*Phacops*) fragments. Preservation is as limonite-filled molds and casts.

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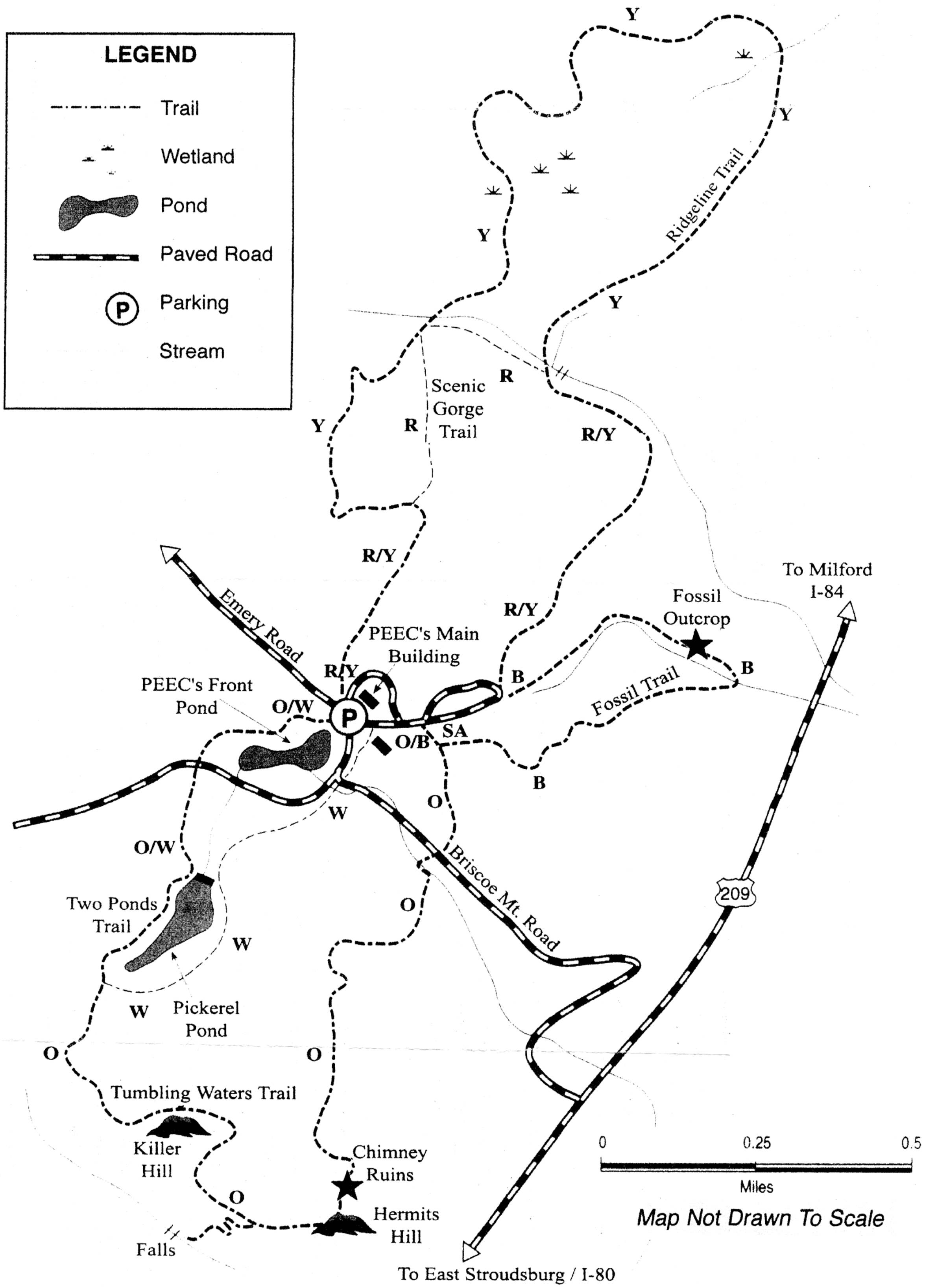
Figure 1. PEEC trail map. Lunch will be at the Pavilion (marked 'SA' on this map). The Fossil Trail is a 1.25 mile loop, but the quickest access to the main fossiliferous outcrop on the Fossil Trail (marked by a black star on this map; trail marker #14) is from the northern end of the trail; the trailhead is across the grassy area and pond, on the far side of the campfire site. Fossil Trail is marked by blue blazes. (Modified from PEEC trail map.)


LEGEND
Trail
Wetland
Pond
Paved Road
Parking
Stream
Y
Ridgeline Trail
R
Scenic Gorge Trail
R/Y
To Milford I-84
Fossil Outcrop
Fossil Trail
B
Emery Road
PEEC's Main Building
PEEC's Front Pond
O/W
SA
O/B
W
O
Briscoe Mt. Road
209
Two Ponds Trail
Pickerel Pond
Tumbling Waters Trail
Killer Hill
Chimney Ruins
Hermits Hill
Falls
To East Stroudsburg / I-80
0
0.25
0.5
Miles
Map Not Drawn To Scale

STOP 4: RUBIN HILL ROAD, MONTAGUE, NJ

Arlene Castleman[1] **and Emma C. Rainforth**[2]
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Limited collecting is permitted at this outcrop.
This outcrop is on residential property; the owner has graciously permitted us access.

LOCATION

Milford, PA-NJ 7.5-minute Quadrangle.
This outcrop is on a residential property; permission to visit must be obtained from the landowner at 36 Rubin Hill Rd.

INTRODUCTION

Prior to residential development, this rise was a popular collecting spot for amateur and professional paleontologists. Outcrops remain accessible (with landowner permission) and float specimens are common.

PALEONTOLOGY

This site is in the *Acrospirifer murchisoni* zone of the Lower Devonian Oriskany Group (Ramsdell 1970). Within the Delaware Water Gap NRA, this unit contains corals, brachiopods, bivalves, gastropods, ostracods, trilobites, and crinoids (Albright 1987). We have observed gastropods, trilobites, brachiopods, and bivalves at this location.

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STOP 5: GINGERBREAD CASTLE STROMATOLITES, HAMBURG, NJ

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Collecting is not permitted at this outcrop.
Leave hammers in the buses.

LOCATION

Hamburg 7.5 minute quadrangle.
This spectacular outcrop is on private property; permission to visit must be obtained from Diversified Communities. Hammering is not permitted (and would ruin the outcrop for future visitors).

Use caution on the outcrop; surfaces are steep and may be slippery. Excellent examples of features described may be seen at the base of each slope.

INTRODUCTION

This spectacular outcrop is of stromatolitic Allentown Dolomite (Middle Cambrian – lowermost Ordovician), a shallow water, nearshore carbonate that was periodically subaerially exposed. Dolomitization of the original carbonate preserved many of the original textures (Monteverde 2004). The outcrop consists of 'whalebacks' – roche moutonnées carved by glaciers, with the strata dipping to the northwest (Figure 1).

Figure 1. View of outcrop prior to present construction. Ground level is currently slightly lower and the right end of the outcrop has been removed, permitting examination of the outcrop in cross-section.

STROMATOLITES

Stromatolites are ‘discrete, in-place structures with recognizable boundaries that are characterized by “gravity-defying” internal laminae reflecting addition of material to a discrete surface’ (Demicco and Hardie, 1994, p. 104). These cyanobacterial three-dimensional laminated structures first appeared ~3.5 Ga, peaking 1.65 – 0.65 Ga; they declined dramatically after the Early Ordovician, coinciding with the increase in epifaunal grazers and burrowers (Demicco and Hardie 1994). They are generally classified as 1) laterally linked hemispheroids, 2) discrete vertically stacked hemispheroids or 3) discrete spheroids (Logan *et al.,* 1964). Combinational forms also exist. The term thrombolite (Aitken, 1967) was proposed for structures without discrete laminations. Stromatolites today form in a variety of settings, including shallow subtidal, intertidal and supratidal marine environments or in saline lacustrine environments. In salt ponds these features tend to be flat laminations instead of a more three dimensional feature (Cornee *et al.* 1992).

The stromatolites (Figure 2) observed at this site are of the discrete spheroidal type, which tend to correlate with higher energy environments. The higher energy environment is also reinforced by the many storm layers present throughout the outcrop (Figures 3, 4). These storm layers are rich in ooids .

Figure 2. Close-up of a portion of the uppermost bedding plane in the outcrop. In the center of the picture a collapse breccia is visible (see also Figure 3): material that fell into a cavity following minor dissolution. Immediately overlying this layer are mudcracked carbonates, visible in darker area in lower right portion of photograph; these indicate subaerial exposure at this time. Glacial striations are clearly visible in most of this photograph. Pencil for scale (adjacent to lower left stromatolite).

Figure 3. Oolitic layers; the lower darker-colored layer contains small ooids while the upper layer bears much larger ooids. Dark gray rip-up clasts occur near the interface of the two layers.

Figure 4. Edgewise conglomerate; pebbles are ripped up form underlying layers.

Figure 5. Cross-sectional view of a collapse breccia associated with dissolution of material in-between stromatolite mounds.

Additionally, these mounds appear to be cut by tidal channels and this can cause slumping that is filled by bioclasts and lithoclasts which were originally reworked desiccated tidal flat sediments (Figures 2, 5). Analogous conditions are presented by Wilson (1975) from the Late Cambrian algal mounds of central Texas (Llano Uplift) as well as other areas throughout the edges of the North American craton. The outcrop also includes desiccation cracks (Figure 2), which supposes an intertidal to even supratidal environment. Desiccation cracks are characteristically associated with microbialites in peritidal environments (Burne and Moore, 1987). Both cyanobacterial and algal mats can be responsible for the formation of desiccation cracks in dolomitic sediments in the modern tidal flats of the Bahamas (Mitchell and Horton, 1995).

Diagenetically, the outcrop shows extensive stylolites and fenestral porosity. Stylolites are pressure solution secondary sedimentary structures, while fenestral porosity and bird's eye structures are syndepositional structures mainly found in supratidal algal related mud dominated sediments (Moore, 1989).

PALEOENVIRONMENTAL INTERPRETATION

We interpret this outcrop as having been formed in nearshore to marginal marine conditions (Figure 6). The presence of mudcracks, birds-eye structures, and tidal channels indicate subaerial exposure; the stromatolites and oolitic carbonates would have formed in shallow water. The section records several such fluctuations in base level.

GLACIAL FEATURES

The whaleback outcrops are glacially-carved roche moutonnées. Glacial striations are evident over most of the polished surfaces (Figure 1), and (along with the outcrop orientation) indicate direction of glacial flow. In places, chatter marks are visible.

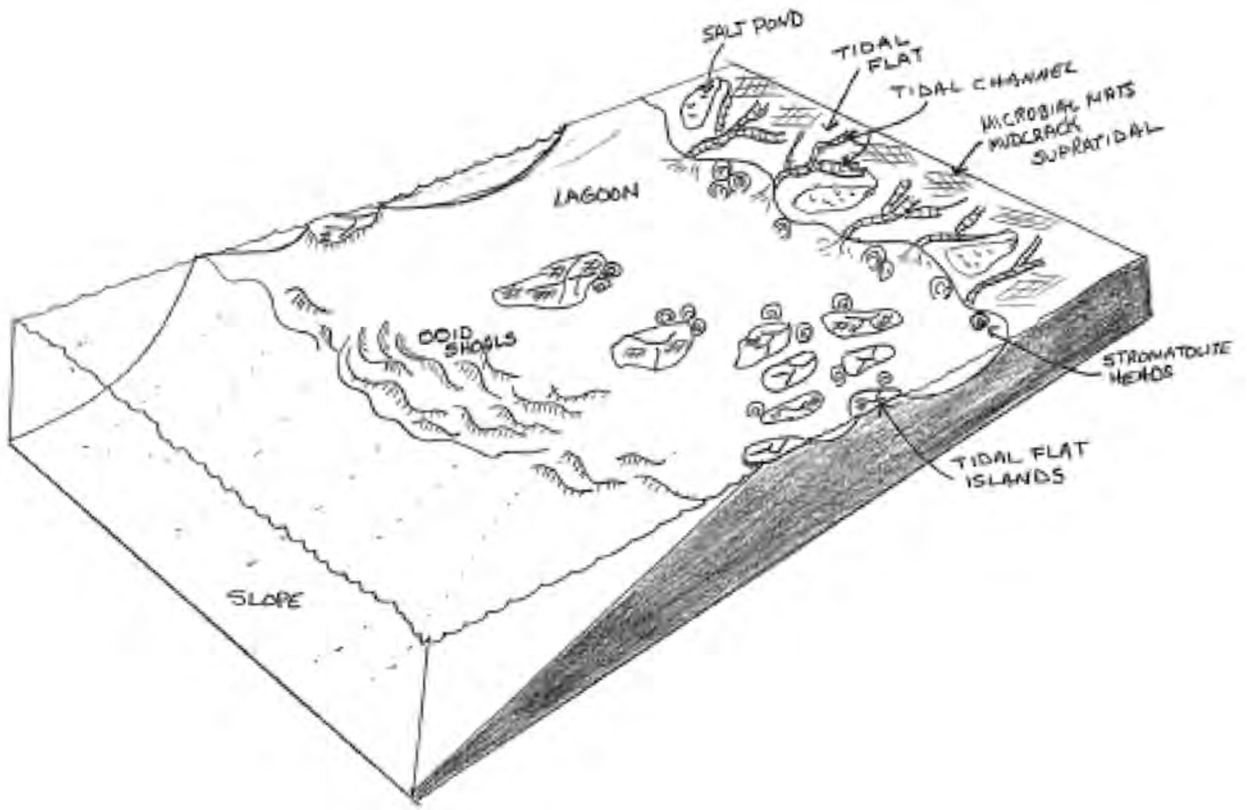
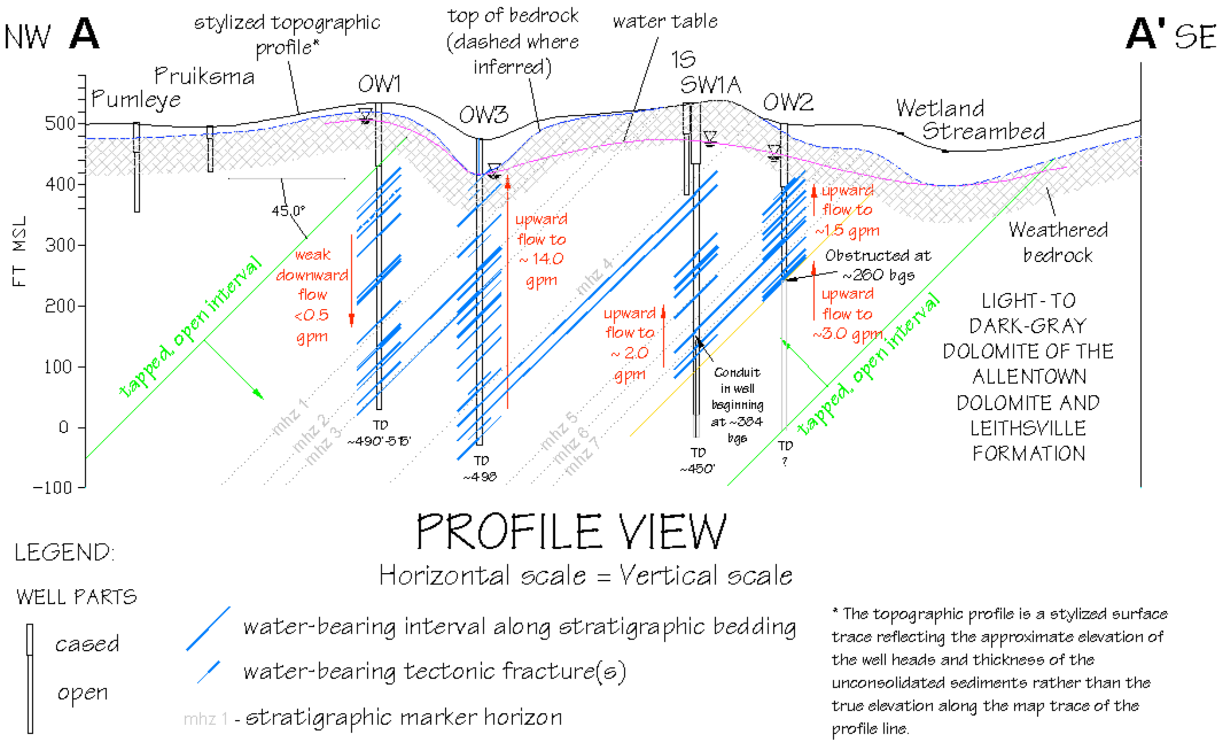


Figure 6. Paleoenvironmental reconstruction of the Gingerbread Castle stromatolite site. (Modified from Pratt et al., 1992.)

HYDROGEOLOGY

A hydrogeological framework study was conducted by the New Jersey Geological Survey at this development as part of a ground-water supply investigation. The well field at the development includes one 8-inch diameter supply well and five 6-inch diameter observation wells in bedrock. The bedrock aquifer is composed of the lower part of the Allentown Dolomite and the upper part of the Leithsville Fm. A profile view (Figure 7) of the hydrogeological framework was constructed based on optical televiewer, fluid-temperature and electrical-conductivity, caliper, heat-pulse flowmeter, and color video (VHS) borehole geophysical logs. Stratigraphic bedding and tectonic fracture orientations were measured using an optical televiewer.



* The topographic profile is a stylized surface trace reflecting the approximate elevation of the well heads and thickness of the unconsolidated sediments rather than the true elevation along the map trace of the profile line.

Figure 7. Hydrogeological framework of wellfield.

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