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PROCEEDINGS OF A SYMPOSIUM,
FIELD TRIPS AND TEACHER WORKSHOP
ON THE TOPIC

CONTRIBUTIONS TO THE PALEONTOLGY OF NEW JERSEY

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ACKNOWLEDGEMENTS

The concept for this year's "G.A.N.J." meeting began two years ago when Mike Hozik (Stockton State) asked me to run for President Elect. At that same meeting (N.E.G.S.A.-Vermont), within the hour I was discussing what course of action to pursue with John Pojeta and his wife, Mary Lou. John was then the Chief of Paleontology and Stratigraphy at the U.S.G.S. and has continued to help me "stay the course".

New Jersey has had a prolonged need for a publication to update important research in the area of paleontology within the state. G.A.N.J. provides the perfect implement to solve the issue. Increasingly, we, as an organization, will have to "take up the slack" created by government downsizing. It is not only our responsibility for our future to do so, but it is our obligation for future generations to come.

Many people helped to bring this diverse volume to fruition. I would like to than them here, individually. First to **Stephen Hall**, Dean of the School of Health and Science at William Paterson College and **Richard Pardi**, Chair of the Department of Environmental Science and Geography; both graciously offered our campus for the site of the G.A.N.J. XII - 1995 meeting. To **Beverly Middleton**, the Department Secretary, who assumed the tremendous responsibilities of organizing the hotel accommodations, the banquet, the details of the symposium and the buses for the field trip. Without her help I would have been completely lost. To the **Executive Committee** (listed on the next page) who met tirelessly and selflessly to bring about this collaborative effort. Their labors usually go unnoticed and too often, without thanks. The three corporate sponsors (on the inside front cover) made the publication of very expensive half-tones possible. My contact people in the organizations were of invaluable assistance and I wish to acknowledge them at this time: **Linda Kimler** (Riverdale Quarry and Millington Quarry), **Joanne DiNicola** and **Tony Pio Costa** (Pio Costa Industries) and **Charlie** and **Hank, Jr., Shotmeyer** (Shotmeyer Brothers). To **Marge Gay** and **Irene Everett** who typed my manuscript. To my wife, **Sharon**, who answered numerous questions about formats, typed letters and took dozens of telephone messages. To my son, **Christian Silano** who designed the cover and to my other son, **Jason Silano**, who ran numerous errands for me. To **Scott Ryan** of the WPC Natural Science Club who offered logistical help on the day of the symposium. And last, but not least, to the **Authors** and **Co-authors** of the manuscripts who gave their foremost. I chose the finest members in the field of Paleontology and they all came through with "Flying colors". In doing so, they have provided us with a timely and enduring reference book. To them and to all others I have mentioned, I extend a sincere and heartfelt thank-you.

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COLLECTING FOSSILS

John Pojeta, Jr.

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John Baker asked me to speak on collecting fossils when he was first organizing this symposium. Some of you may know that for the past 15 years I have been involved in a number of venues dealing with concerns that have arisen about collecting fossils. I have published information on these concerns in *Palaios* (1988), *American Paleontologist* (1992), *Geotimes* (1993a, b), *Priscum* (1995), *The Proceedings of the Northern Plains Governors' Conference on Fossils for the Future* (1993c), and I was a member of the National Research Council's "Committee on Guidelines for Paleontological Collecting," which produced a publication entitled *Paleontological Collecting* (1987). For this presentation, I will spend a short time telling you about some of my perspectives on fossil collecting and then open today's venue to listen to your questions, comments, experiences, and perspectives on the do's and do not's of collecting fossils. This approach will continue my education in this major area of concern to all persons interested in fossils; I hope it will begin an ongoing dialog between all of us and that you will discuss the issues with persons that you know who are not at this symposium. I have arranged the talk into a series of memorandumlike bullets.

STARTING POINTS---I think almost all of us involved in collecting fossils can agree that: (1) In order to collect, we need the permission of the person in charge of the locality, be that a private land owner, local, state, or federal land manager, tribal official, etc. (2) Over about the past 20 years, collecting fossils has become increasingly complicated. As fossil collectors, all of us know tales of these complications, or we have experienced them first hand.

Beyond these two generalizations, almost every collector of fossils has his/her perspectives on the proper do's and do not's of the process. These points of view range from the extremes of: (1) Only professional paleontologists should collect fossils, and laws and rules should be developed to prevent and punish anyone else from doing so, to (2) Anyone should be allowed to collect fossils (Retallack, 1993).

WHAT IS A PROFESSIONAL PALEONTOLOGIST?---In all of the debates about who should be allowed to collect fossils, the term professional paleontologist comes up. Often it comes up in the context mentioned above---that only professional paleontologists should be allowed to collect fossils. Sometimes it appears as---a professional paleontologist should have oversight of any collecting done at a particular locality. Yet, determining who is or is not a professional paleontologist is difficult to agree upon, and there is no organization that registers or accredits people as professional paleontologists. One of the standard definitions is "A professional paleontologist is a person who makes her/his living studying fossils;" conversely an "amateur paleontologist is one who collects fosils but does not make his/her living studying fossils."

Such definitions do not allow amateurs to achieve peer status with professionals, and such definitions would reduce some major paleontological researchers to the status of amateurs. For example, Franco Rasetti was professor of physics at Johns Hopkins University; however, his major research interest was trilobite taxonomy and biostratigraphy and he was a leading scholar of his generation in this field. Jack McIntosh, the leading scholar of sauropod dinosaurs was professor of physics at Wesleyan University in Connecticut. Karl Hirsch was a machinist at Rocky Flats, Colorado, before he became the world's leading authority on fossil eggs. In paleontology, there is a continuum of workers ranging from casual amateur to National Academy of Sciences professional.

IS FEDERAL LEGISLATION NEEDED?---In the past year there have been three proposed bills waiting introduction in the Congress of the United States dealing with collecting fossils on the public lands. There was an attempt to introduce one of these bills in the previous Congress.

Generally, the term public lands is used to identify the hundreds of millions of acres managed by federal agencies such as the Bureau of Land Management and the National Park Service in the U.S. Department of the Interior and the U.S. Forest Service in the U.S. Department of Agriculture; most of these public lands are west of the Mississippi River. However, various other federal agencies manage land including the Department of Defense, Tennessee Valley Authority, Department of Energy, Postal Service, Federal Highway Administration, Department of Veterans Affairs, various agencies that deal with coastal waters and navigable rivers and streams, etc. Most of these agencies impact land ownership nationwide. If one adds to these federal agencies all of the state, local, and tribal agencies that manage lands, it can become a daunting task just to find out from which one to ask permission to collect. It would probably be best to redefine the term public lands to include all lands managed by or for any governmental entity, federal, state, city, county, and local, and to use qualifiers such as federal public lands, state public lands, etc. Native American lands are a unique category about which I am not qualified to speak.

To the question, "is new federal legislation needed to manage fossil collecting on federal public lands?"---I say probably not, because there already seems to be enough authority to manage fossils for these. In 1987, the National Research Council Committee on Guidelines for Paleontological Collecting published its report. That committee included two lawyers who researched all federal and state laws that might apply to fossil collecting. One of the conclusions of this research was (p. 216):

> "... ample statutory authority exists for the various federal land management agencies to protect, manage and dispose of fossils on public lands. However, with few exceptions, existing statutes do not impose a duty on federal agencies to manage or preserve fossils on public lands. Among the exceptions to this general statement are specific statutes establishing national monuments for the purposes of preserving fossil remains. Thus, the issue of whether federal agencies should regulate scientific or amateur fossil collecting by means of a permit system is largely a policy question, rather than a legal question. Fossil collecting for commercial purposes, however, probably requires some kind of permit system under existing law to ensure payment of adequate compensation."

If enough laws already exist, why create more?

IS A PERMIT SYSTEM NEEDED?---My answer to this question is yes and no. It depends on what the fossil collector wants to do. I think we can all agree that collecting at places like Dinosaur National Monument and Fossil Butte should require a permitting process. However, casual surface collecting on lands dedicated to multiuse purposes, such as most Bureau of Land Management and U.S. Forest Service land, should not require a permit process.

In this second case, notification to the local land manager, either in writing or by stopping at his/her office, should be done for any of several reasons, such as: (1) so that the collector can learn to stay away from a certain area because it may contain a protected species, (2) an area may be a breeding ground for a particular species that is in season, (3) an area may contain archeological sites that cannot be disturbed or collected, (4) an area may have been set aside for a particular scientific study, (5) because notification is courteous, (6) in some isolated areas, it is prudent to let someone know where you are for a variety of reasons ranging from weather to injury. A notification process is less formal than a permit process and it builds trust between the land manager and the fossil collector, because the land manager knows what is happening on the land that she/he is managing.

TO WHOM DO THE FOSSILS BELONG?---The January-February 1994 issue of the British journal *Geology Today* (p. 6) contained the following news item:

> "**Collect a fossil, go to jail:** In 1992, US Senator Max Baucus, aided and abetted by the Society for Vertebrate Paleontology (SVP), introduced a bill into Congress that would have made fossil-collecting in the USA illegal except by a few registered academics. The bill never made it to the vote. As *Science* (v.262, p.323, 1993) reports, however, the SVP did not

give up. A new version of the bill is being drafted by Senator Baucus. Broadly, similar to the previous one, it will forbid the collection and sale of fossils, except by the favored academics, and---to make the bill more acceptable to opponents---amateurs under very limited circumstances. The aim of the bill's proponents is to stamp out commercial and most amateur collecting, but museums have come to see just how much of a threat it is to them. Many (most?) museums, having very limited or zero expedition budgets, rely on 'commercial' and amateur collectors to build up their collections. But there is an even greater sting in the new bill. Ownership of all fossils will be vested in a public 'trustee'. If the trustee is to be the US government, as seems likely, any drilling into bones or destructive analysis of any kind on fossils would automatically become illegal because such work would be damaging public property, a crime."

At the time of this writing, no new statute dealing with fossil collecting has been introduced on the floor of the current Congress. Clearly, the proposed draft bill cited above would have major impacts on fossil collecting and collectors; our community needs to more aware of proposed legislation dealing with fossils and collecting. Various persons have already experienced the difficulty of donating specimens to certain museums, because the institutions now want very detailed information on land owners' permission to collect the specimens; such information can be difficult to obtain for specimens collected many years ago.

As far as I can determine, the only federal laws that directly make mention of fossils and/or paleontology are: (1) The U.S. Geological Survey enabling act of 1879; (2) The Petrified Wood Act of 1962; (3) The Archeological Resources Protection Act of 1979; this Act's definition of "archeological resource" excludes nonfossilized and fossilized paleontological specimens, unless found in an archeological context; and (4) Collection of petrified wood for commercial purposes is governed by the 1947 Materials Act and the regulations pertaining to mineral material sales. The National Research Council report on paleontological collecting summarizes these acts.

COMMERCE IN FOSSILS?---A great deal of the debate about collecting fossils has revolved around fossils as items of commerce. In my opinion this issue has been overhyped; there is little if any documentation of fossils selling for millions of dollars. I do know of a fully prepared and mounted composite skeleton of a Cretaceous hadrosaur that was sold to the National Museum of Wales for $350,000. The firm that sold the specimen estimated that it took 20,000 hours to prepare and mount it, or about $17.50/hour.

Many of us can remember when museum shops sold real fossils, and I can remember buying some. Today, almost no museum shop sells real fossils. Yet, in my opinion, there is a need to sell various common fossils for education, both in and out of the formal education system. There is something very special to the human psyche in holding, measuring, describing, and admiring a real fossil, which cannot be obtained from a museum display or a replica. Also, I have had the experience of taking young and old, students and nonstudents, into the field to collect fossil shells; this provides an even greater boost to the psyche, because they are finding fossils for themselves.

Certain rare fossils should not be sold for nonscientific purposes. For example, any new specimen of the Burgess Shale onychophoran *Aysheaia pedunculata* should be made available to the scientific community. However, the common Ordovician brachiopod *Platystrophia ponderosa* can be used both in the laboratory and field for instruction in taxonomy, ecology, biostratigraphy, and sedimentation to everyone interested in fossils.

Commerce in fossils includes bartering, which is widely practiced among collectors of fossils. Barter represents one end member of commerce in fossils. The other end member is represented by quarrying of almost any sedimentary rock for facing stone, road metal, decorative stone, and fuel, such as the large open-pit coal mines. My laboratory windows look out at the main building of the Department of Justice, which is faced with fossiliferous limestone from Indiana, as are most of the buildings in the Federal Triangle in Washington D.C.

Also, the issue of commerce in fossils seems to be closely tied to jingoism about American fossils. This jingoism extends to smaller and smaller political entities. "American fossils should stay in America," "Rhode Island fossils should stay in Rhode Island," "Calvert County fossils should stay in Calvert County," etc. Such statements ignore several aspects of the organization of paleontology---(1) American fossils in the collections of a museum in Wales are fully available for study by any scientist who wishes to examine them, and if they are on display, they have enormous educational value if such fossils do not occur in Wales. (2) Paleontology is not organized on national, state, or county lines; commonly, a leading specialist in a fossil group works in a different state than the one in which she/he collects specimens. This is simply a matter of where one gets a job versus where one's research interests lie. (3) All American paleontologists desire to have comparative material from other parts of the world, otherwise their work becomes parochial. How do we get comparative material, if we are not willing to exchange with others?

ARE BONES AND TEETH SPECIAL?---A large part of the debate about, and the attempts to limit, fossil collecting have been driven by students of vertebrates. From my viewpoint, there are several shortcomings to how the debate has progressed. (1) No definition of vertebrate fossils has been provided, and it now seems likely that the extremely abundant, widespread, and geologically very useful conodonts are vertebrates (Sansom, and others, 1992). (2) Not all vertebrate fossils are rare and not every scrap of bone or tooth is a scientific icon. (3) There are many invertebrates and plants that are rare, as are many Precambrian microfossils and megafossils.

FOSSILS ARE NOT ARTIFACTS!---A major problem for collectors of fossils is the confusion among both the public and many decision makers of paleontology with archeology. I have long since lost count of the number of times someone has begun discussing artifacts when I tell them that I am a paleontologist. The vast majority of people have no experience in collecting fossils, do not understand that fossils are a part of the rocks, that some rock units are almost entirely made of fossils, and that paleontologists deal with the record of life on Earth for the past 3.5 billion years.

Archeology deals with the remains and handiwork of one group of primates whose known maximum fossil record is about 25 million years. The known fossil record of the human family covers about 3.5 million years. Generally human fossils are rare and recovered with different field techniques than most other fossils; human handiwork consists of things that are put into or on top of the rocks rather than being a part of the rocks.

JUDGMENT AND KNOW-HOW---Paleontology and fossil collecting cannot be treated with a checklist approach. It takes judgment and know-how to determine what to collect, what is rare, what should be placed in a museum, and what is the scientific value of a specimen. This judgment and know-how are not acquired in a 90 day crash course in paleontology, and they cannot be reduced to a checklist.

Within the federal government, the U.S. Geological Survey can provide the experts having the judgment and know-how needed by federal land managers. U.S. Geological Survey paleontologists should be included in the land managing process from the very beginning, and not after decision making has become far advanced.

EDUCATION VERSUS PUNISHMENT---As a group, collectors of fossils need to expand their educational outreach efforts enormously. The public needs to understand the differences between paleontology and archeology. The public needs to know that there is more to paleontology than dinosaurs. The public needs to know that not all big tetrapods are dinosaurs; I remember being in the Smithsonian's Pleistocene exhibit hall at a time when the dinosaur hall was closed for renovation and hearing a parent tell some kids that the giant ground sloths were dinosaurs. Examples of the need to educate people about paleontology could be multiplied. Collectors of fossils must address this need, or collecting fossils will continue to become more complicated.

At best, educating the public about all fossils is a slow process. Some paleontologists and decision makers have tried another approach. One of the possible federal legislative bills mentioned above includes criminal penalties for collecting fossils. The maximum penalty was five years in jail and a fine of $100,000. In my opinion, this approach might catch a few persons trying to profit from selling fossils; however, most likely it will catch people who casually collect a fossil as a keep sake for a vacation trip to the western lands.

WHO SHOULD BE ALLOWED TO COLLECT?---I have consistently advocated a place at the table for each of the constituencies interested in collecting fossils. These includes professional paleontologists, amateur paleontologists, educators, and commercial collectors. In my opinion, each group needs a process to obtain access to the land to pursue the group's interests. Moreover, each group needs a different process and different oversight. As an example, a college field course in geological mapping techniques needs to let students learn first hand how to use fossils to interpret past geological events, and would have a different process than would commercial collectors who want to sell fossils to museums. Likewise, a 4-H Club leader wanting to give youngsters a natural history experience collecting fossils would have a different process than a professional paleontologist conducting research. A family from New Jersey taking a vacation to the western lands should not be punished for casually picking up a rock containing fossils.

Giving each constituency a distinct process to follow in pursuing its interests fosters having each following the rules.

OTHER SCIENCES AND LAND MANAGERS---In May 1995, I attended a two day planning meeting at the National Research Council. The meeting dealt with Scientific Studies on Public Lands, and whether or not the National Research Council should attempt to conduct a major study of this area. I quickly learned that paleontology is only one of many sciences that are impacted by land managment decisions. For example, John Eichelberger, professor of volcanology, University of Alaska, Fairbanks, told us of his experience in trying to drill into Novarupta Volcano, Katmai National Park, in the Valley of Ten Thousand Smokes; John wanted to drill down the "throat" of the volcano. Scientifically the project was easily defendable and was supported by the Department of Energy, National Science Foundation, and U.S. Geological Survey. However, the question arose should drilling and mechanized equipment be permitted in a national park and wilderness area? Three years were spent in providing information to the National Park Service, including spending about $1,000,000 and producing an Environmental Impact Statement. In the end the National Park Service decided it did not have authority to permit the project, that such authority had to come from Congress, and the Environmental Impact Statement was never published.

We were given documents about the work of Professor Marcia McNutt, Columbia University at Lake Mead and what she had to do to obtain a Special Use Permit from the National Park Service for a seismic reflection survey of the lake. We also received information about the Mount Graham telescope and the Mount Graham squirrel in Arizona and the application of the Endangered Species Act.

Examples could be multiplied, but the above show that a variety of sciences needing field data or space are impacted by land managing decisions.

DO WE DIFFER FROM OTHER SPECIAL INTEREST GROUPS?---The scientific disciplines represented at the National Research Council planning session in May 1995 included an interesting mix of ecology, oceanography, volcanology, paleontology, geophyics, political science, rural sociology, forestry, and land policy. Sally Fairfax, Professor, University of California, Berkeley, a political scientist, gave us the opinion that scientists are just another interest group wanting access to the federal public lands.

By my reckoning she is correct. Land managers must deal with numerous and sometimes conflicting claims to the use of the land. Grazing interests, mining interests, recreational interests, wilderness interests, scientific interests, and others, all must be dealt with by the land managers. Sometimes these interests conflict and sometimes what is desired must be refused because it violates laws or regulations.

Some of these interests can be dealt with by checklist and inventory procedures. However, in my opinion, fossil collecting cannot be dealt with by checklist and inventory procedures. The paleontological value of a locality or a specimen requires interpretation, that is judgment and know-how. The expertise for making these interpretations already exists in the federal government and should be put to use by the land managers.

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Parastirpulina sohli: A NEW CRETACEOUS CLAVAGELLID PELECYPOD

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Washington, D.C., and Monmouth Amateur Paleontological
Society, West Long Branch, New Jersey.

ABSTRACT.--The new genus and species *Parastirpulina sohli* is described from the Navesink Formation (Maastrichtian) of New Jersey. The species also occurs in the Tombigbee Sand Member, Eutaw Formation (Santonian), of Mississippi. *P. sohli* is the second clavagellid species known from the Cretaceous rocks of North America. *Parastirpulina* is compared to the other known genera of Cretaceous clavagellids. Cretaceous and Holocene species of *Stirpulina* Stoliczka are figured.

INTRODUCTION

Generally, fossil clavagellids have been described in studies devoted to other purposes; a few authors considered fossil species (Smith, 1962). Recently, a number of authors have written papers specific to fossil clavagellids, including Fenninger & Wassermann (1982), Savazzi (1982a, b), Pojeta & Sohl (1987, 1988), Jones & Nicol (1989), Mayoral (1990), Majima (1991, 1994), and Stallwood (1995). The purpose of our paper is to describe a new genus and species of Late Cretaceous clavagellids.

The specimens of *Parastirpulina sohli* described here were collected by Ralph Johnson and Penny Dillon from the Navesink Formation of New Jersey. The Navesink is Maastrichtian in age (Pojeta & Sohl, 1987) and lies unconformably on the Mount Laurel Sand. Both formations also have yielded the clavagellid *Ascaulocardium armatum* (Morton), 1833. Elsewhere, *Parastirpulina sohli* is known from the Tombigbee Sand Member of the Eutaw Formation (Santonian) of Mississippi (Pojeta & Sohl, 1987) where it also occurs with *Ascaulocardium armatum*.

For comparison with *Parastirpulina sohli* we figure the Cretaceous species *Stirpulina elegans* (Müller) from its type area near Aachen, Germany and the living species *S. ramosa* (Dunker). The terminology used for describing clavagellids follows Savazzi (1982a, b) and Pojeta & Sohl (1987).

Repositories.--The specimens of *Parastirpulina sohli* described here are in the collections of the Department of Paleobiology, U.S. National Museum of Natural History, Washington, D.C. (USNM). The specimen of *Stirpulina elegans* was borrowed from the Institut royal des Sciences naturelles de Belgique, Brussels (IRSB). The specimens of *Stirpulina ramosa* were borrowed from the Division of Mollusks, U.S. National Museum of Natural History (USNMDM), and the Academy of Natural Science, Philadelphia, PA (ANSP).

Acknowledgments.--Several people helped us with this study; we thank them all. Annie Dhondt, IRSB, lent us the specimen of

Stirpulina elegans and M.A. Garback, ANSP, lent us specimens of *Stirpulina ramosa*. J.E. Baker made the study possible by organizing this symposium. J.M. Berdan and W. A. Oliver, Jr. (USGS), provided timely and helpful reviews of the manuscript. Marija Balanc (USGS) provided the photographs. We give special thanks to the late N.F. Sohl for friendship, knowledge, and patience through many conversations about clavagellids.

SYSTEMATIC PALEONTOLOGY

Family **Clavagellidae** d'Orbigny, 1844

Definition.--Pholadomyoids having nacreous juvenile shell, free when young, one or both valves cemented to adventitious elongate nonnacreous crypt in adult, aragonitic. Juvenile shell equivalved and somewhat to strongly inequilateral. Adventitious crypt composed of two to many parts; anterior end commonly sealed by a perforated plate, tubules, or tubes; posterior end may have siphonal collars. Adult size usually ranging from 30 to 250 mm, can reach 1,000 mm.

Adult having two subequal adductor muscles, or adductor muscles absent. Pedal muscles reduced to vestigial. Pallial and siphonal muscles well developed. Siphons long and fused. Ligament usually external, opisthodetic, often mounted on nymphs, may have lithodesma, or may be internal, amphidetic, and supported by chondrophores. Hinge teeth absent.

Stratigraphic range.--Upper Cretaceous (Cenomanian) to Holocene. The known Cenomanian and most Turonian specimens are too poorly preserved to be assigned to genera.

Genus ***Parastirpulina*** n. gen.

Type species.--*Parastirpulina sohli* n. sp. is here designated the type species of the new genus *Parastirpulina*.

Diagnosis.--Clavagellids having an adventitious conch with many grooves, swellings, and tubules covering the free right valve. Left juvenile shell cemented to adventitious crypt.

Definition.--Small clavagellids, maximum known length 77 mm; ornament of juvenile shell is comarginal broad shallow rugae and growth increments. Juvenile shell with free right valve that is covered by adventitious crypt; left valve cemented to adventitious conch, but not covered by it. Juvenile shell having subequal adductor muscle scars, pallial sinus, and pallial line, which may have continuous or bundled attachment scars; pedal muscle scars reduced; hinge and ligament unknown. Adventitious conch complex, having an anterior corona of tubes (as in *Stirpulina*), a posterior siphonal sheath, and a adventitious crypt cover of the right valve. This cover has the typical triple junction of taxa with a free right valve and a complex series of swellings, grooves, and tubules.

Stratigraphic distribution.--Upper Cretaceous, Santonian to Maastrichtian.

Geographic Distribution.--New Jersey and Mississippi.

Etymology.--The generic name is derived from the Greek *para*, meaning beside or near, and the generic name *Stirpulina*, because of similarities to that genus.

Comparison.--*Parastirpulina* is conchologically like the three other known genera of Cretaceous clavagellids in having a free right valve juvenile shell and a left valve cemented to the rest of the crypt. Stratigraphic occurrence indicates that this is a primitive condition in clavagellids.

Major differences between the four known Cretaceous genera are: (1) *Clavagella* Lamarck lacks an anterior corona of tubes. It has short tubules along the margins of the juvenile valves. The oldest known species is *C. semisulcata* Forbes (Pojeta and Sohl, 1987, Figure 37.19-37.22), from the Valudavur Group (Campanian to Maastrichtian) at Pondicherry in southern India. Living species are both burrowers and rock borers.

(2) *Ascaulocardium* Pojeta and Sohl lacks an anterior corona of tubes, instead it has four elongated anterior tubes about equal in length to the rest of the crypt, and it has a posterior crown of tubes (Pojeta and Sohl, 1987, Figure 6). The only known species is *A. armatum* (Morton), which has a Santonian to Maastrichtian range, and is known only from the eastern Coastal Plains of the United States (Pojeta and Sohl, 1987, Figure 39). The known fossils indicate that *A. armatum* was a burrower.

(3) *Stirpulina* Stoliczka has an anterior corona of tubes (pl. 2, figs. 7, 9-11) and a right valve adventitious crypt marked only by growth lines (pl. 2, fig. 8). The oldest known species is *S. saulae* Stallwood (1995, Figure 3) from the Turonian part of the Ladd Formation in southern California. *Stirpulina* has an extensive known fossil record from younger Cretaceous and Cenozoic rocks in Europe (Stallwood, 1995, p. 88). The genus has one known living species, *S. ramosa* (Dunker), 1882, which is a burrower from the Holocene of Japan.

(4) *Parastirpulina* has an anterior corona of tubes (pl. 1, figs. 1-3). However, it differs from the other known Cretaceous clavagellid genera in having the right juvenile shell covered with numerous tubules and irregular swellings and grooves of the adventitious crypt (pl. 1, figs. 1, 4, 5). *P. sohli* was probably a burrower.

Parastirpulina sohli n. sp.

Plate 1, figures 1-11

"*Clavagella*" sp. A Pojeta and Sohl, 1987, p. 60, fig. 24.1-4.

Diagnosis.--*Parastirpulina* having juvenile shell about twice as long as high.

Description.--*Parastirpulina* having adventitious crypt with numerous tubes, and irregular grooves and swellings covering the right juvenile shell, an anterior corona of tubes, and a juvenile shell about twice as long as high.

Types and Type Locality.--All known specimens of *Parastirpulina sohli* n. sp. are incomplete phosphatic molds from a lag concentrate bed. The holotype (USNM 486850) is shown on pl. 1, figs. 1-3; its measurements are: length, 77 mm; height, 24.3 mm; and thickness (both valves), 19.7 mm. The length of the left juvenile shell is 48.6 mm and its height is 23.1 mm. The specimen is incomplete anteriorly and posteriorly. The holotype is from locality 119a of the Monmouth Amateur Paleontological Society, which is an "Exposure on the west bank of Crosswicks Creek, Approx[imately] 1 1/2 mi[les] south of Walnford [New Jersey] and 1 1/4 mi[les] northeast of Arneytown, N[ew] J[ersey]." The type locality occurs on the New Egypt 7.5′ topographic quadrangle.

At the type locality, two rock units are exposed; the lower is the Mount Laurel Sand and the upper is the Navesink Formation The holotype was found in the basal foot of the Navesink Formation, just above the disconformable contact with the Mount Laurel Sand. In addition to the holotype, we figure 7 paratypes (USNM 486851-486857; pl. 1, figs. 4-11) from the type locality; three unfigured paratypes are numbered USNM 486858-486860; some of paratypes were found *in situ* with the holotype, and some were in the scree below the Mount Laurel Sand-Navesink Formation contact. No specimens were found *in situ* in the Mount Laurel Sand, and we assume the specimens found in the scree are from the Navesink Formation.

P. sohli also occurs at locality 119b of the Monmouth Amateur Paleontological Society, which is "Exposures and wash in the small tributary of Crosswicks Creek just east of Hill Road, approx[imately] 1 1/2 mi[les] south of Walnford [New Jersey] and 1 1/4 mi[les] north of Arneytown, N[ew] J[ersey]. (This was the original Nutt Farm site)." One unfigured paratype (USNM 486861) is known from this locality; it too occurs in the basal one foot of the Navesink Formation, just above the contact with the Mount Laurel Sand. Locality 119b is also on the New Egypt 7.5′ topographic quadrangle.

Pojeta & Sohl (1987, Figure 24.1-3 and p. 60) figured and briefly described a specimen of *P. sohli* from the Tombigbee Sand Member of the Eutaw Formation (Santonian) of Mississippi (USNM 419583), as *"Clavagella"* sp. This specimen is also a paratype of *Parastirpulina sohli.*

Distribution.--Upper Cretaceous, Santonian to Maastrichtian. The New Jersey specimens are Maastrichtian in age. The Mississippi specimen is Santonian in age.

Etymology.--*P. sohli* n. sp. is named for the late Norman F. Sohl, in recognition of him and his devotion to the study of Cretaceous mollusks and stratigraphy.

Remarks.--So far as known, *P. sohli* is the only species of the genus *Parastirpulina.* It is one of only two species of clavagellids known from the Cretaceous rocks of North America.

P. sohli mimics the other known North America clavagellid, *Ascaulocardium armatum* (Morton), in its longevity. *Parastirpulina sohli* existed as a genetic unit for about 20 million years according to the estimate of the Santonian to late Maastrichtian time interval given in Harland et al. (1989).

Stirpulina Stoliczka, 1870

Two species of *Stirpulina* are shown on plate 2 for comparison with *Parastirpulina*; comparison can also be made with the fossil species of *Stirpulina* figured by Fenninger & Wassermann (1982), Savazzi (1982a), Mayoral (1990), Bielokrys (1991), and Majima (1994). The primary difference between *Parastirpulina* and *Stirpulina* is in the adventitious crypt covering the free right juvenile valve. Both genera have a corona of tubes supported by a pedestal and the triple junction of the covering of the free right valve. In *Stirpulina* the covering of the right valve is essentially smooth showing only growth increments and agglutinated sediment and shell particles (pl. 2, fig. 8), whereas, in *Parastirpulina* the covering has many tubules and nodes and grooves (pl. 1, figs. 1, 4, 6).

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Explanation of Plate 1

Figures 1-12. *Parastirpulina sohli* n. gen & n. sp.

All from locality 119a; 1-11 X1.5; 12 X3.0.

1-3. Holotype, USNM 486850. 1, Right-lateral view showing adventitious crypt covering of right juvenile valve and triple junction of grooves (arrow). 2, Left-lateral view showing adductor muscle scars, pallial line, pallial sinus, point attachments of mantle anterior to pallial sinus, and pedestal (arrow) and broken tubules of corona. 3, dorsal view (arrow marks reduced anterior pedal retractor muscle scar).

4. Paratype, USNM 486851, right-lateral view having adventitious crypt removed, showing adductor muscle scars, bundled attachments of pallial line and pallial sinus.

5. Paratype, USNM 486852, left-lateral view showing ornament of juvenile shell.

6, 7. Paratype, USNM 486853. 6, Right-lateral view showing adventitious crypt covering of right juvenile shell and triple junction of grooves (arrow). 7, Oblique left-lateral view showing muscle scars, arrow marks reduced posterior pedal retractor muscle scar.

8. Paratype, USNM 486854, right-lateral view of composite mold of juvenile shell showing ornament and pallial sinus.

9. Paratype, USNM 486855, left-lateral view of juvenile shell showing ornament.

10. Paratype, USNM 486856, right-lateral view of juvenile shell showing ornament.

11, 12. Paratype, USNM 486857. 11, Right lateral view showing adventitious crypt covering of juvenile shell. 12, Enlargement of anterocentral part of fig. 11 showing numerous tadpole-shaped extensions from the dorsal and posterior grooves of the crypt. At present, these extensions remain unexplained.


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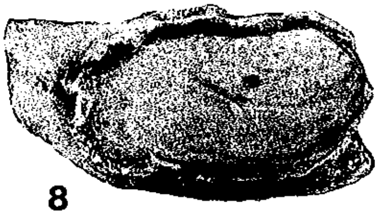
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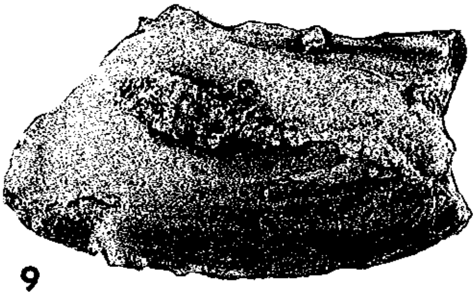
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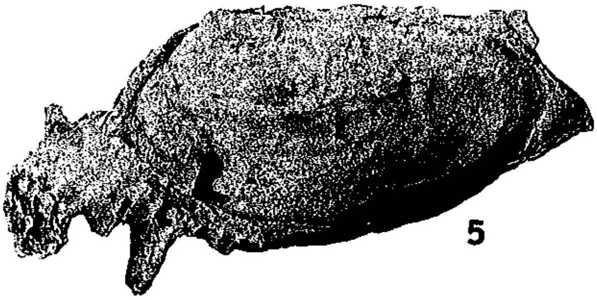
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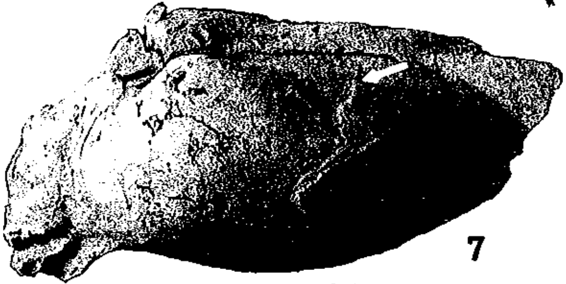
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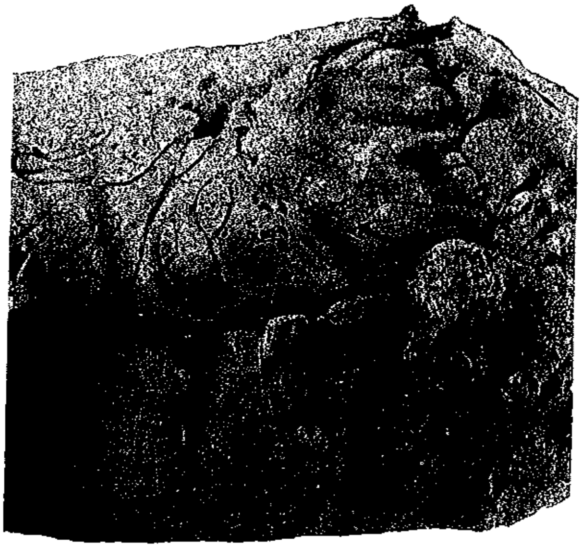
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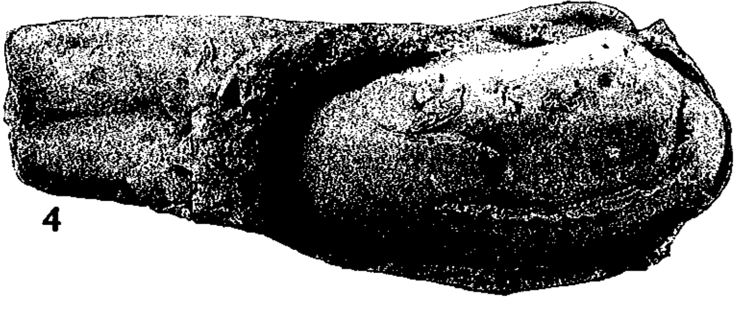
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Parastirpulina

Explanation of Plate 2

Figures 1-6. *Stirpulina elegans* (Müller), 1859.

1, Left-lateral view showing juvenile valve cemented to crypt. 2, Ventral view. 3, Dorsal view. 4, Right-lateral view (all X2.75). 5, Posterior view (X4.5). 6, Anterior view (X4.0). The museum label accompanying the specimen reads "86. Moll. Sec. I. Crét. Et. Campanien Cp2. Hervien. Ass. de Herve (Sable de Vaals). Loc: Vaals (Limbourg). Coll. Ubaghs." IRSB I.G.6521.

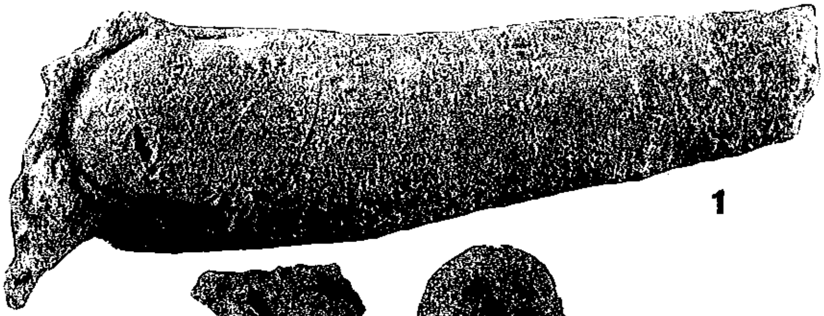
7-11. *Stirpulina ramosa* (Dunker), 1882.

7, 8. 7, Anterior view of corona, detached from rest of crypt (X3.5). 8, Right-lateral view of anterior end showing right valve cover of adventitious crypt; note ornament of growth increments. Arrow marks triple junction of grooves (X2.5). Holocene, locality uncertain, probably southern Japan. USNMDM 880089a, b.

9. Left-lateral view showing juvenile shell cemented into crypt and various parts of crypt having pebbles, sand grains, shell fragments, etc. cemented to it (X2.0). Holocene, Sagami Bay, Japan. ANSP 252287a.

10. Left-lateral view of anterior end showing juvenile shell cemented to crypt and attachment of corona to crypt. Arrow marks pedestal of corona (X3.0). Holocene, Sagami Bay, Japan. ANSP 252287b.

11. Right-lateral view of anterior end showing the right valve cover of the adventitious crypt. Arrow marks triple junction of grooves (X3). Holocene, Sagami Bay, Japan. ANSP 252287c.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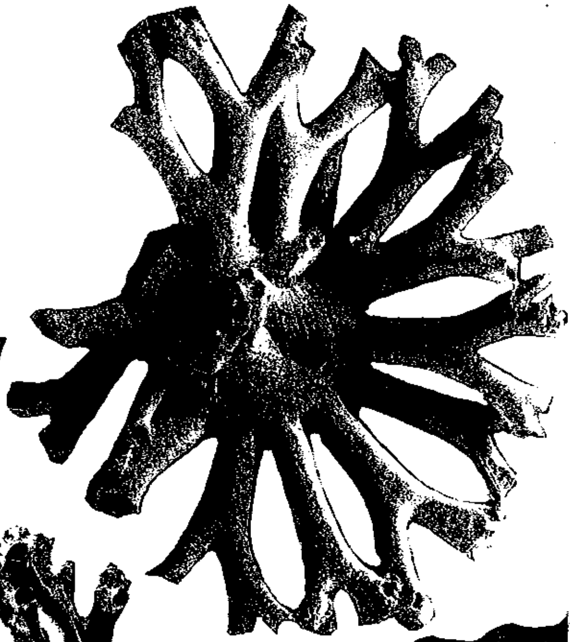
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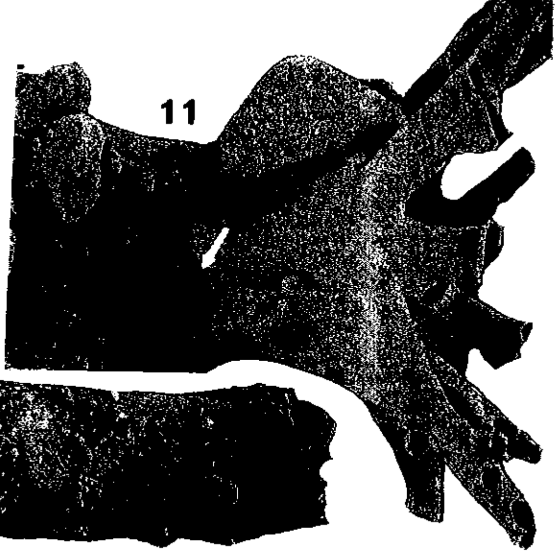
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Stirpulina

Upper Cretaceous Ammonite Faunas of New Jersey

W.J. Kennedy, R.O. Johnson, and W.A. Cobban

Abstract. - The oldest Upper Cretaceous ammonites known from New Jersey come from the Woodbridge Member of the Raritan Formation and indicate a lower upper Cenomanian horizon; they have affinities with both Gulf Coast and Western Interior faunas. There is no ammonite evidence for Turonian, Coniacian or Santonian Stages, although Litwin and others (1993) have recognized Santonian pollen at outcrop. The Merchantville, Marshalltown and Wenonah Formations, Mount Laurel Sand, and basal Navesink Formation yield a series of sometimes remanié faunas that provide an incomplete Campanian record that can be correlated with the Gulf Coast and Western Interior and Western Europe. Macrofossil workers draw the base of the Maastrichtian at a much higher level than those using microfossils; the base of the Maastrichtian in ammonite terms lies low in the Navesink Formation. This unit yields scattered Maastrichtian ammonites representing more than one level that can be precisely correlated with the Gulf Coast and Western Interior sequences. Correlation with Europe and elsewhere is much less precise. The Red Bank and Tinton Sands yield only Sphenodiscus, indicating a Maastrichtian date. The base of the Paleocene Hornerstown Formation yields Maastrichtian ammonites, reworked into Paleocene matrix by physical and biogenic processes.

Introduction

The Upper Cretaceous sediments of New Jersey provide a sporadic ammonite record. A single level of occurrence in the Woodbridge Member of the Raritan Formation can be dated as early Late Cenomanian by comparison with sequences in the Western Interior and Gulf Coast (Cobban and Kennedy, 1990). A more extensive but incomplete Campanian record is known from the Merchantville Formation, Marshalltown Formation, and Wenonah Formation, Mount Laurel Sand, and basal part of the Navesink Formation. A very incomplete Maastrichtian record is known from the higher parts of the Navesink Formation, Red Bank Sand, and Tinton Sand, as well as remanié fossils in the base of the overlying Hornerstown Sand (Figure 1).

The earliest description of ammonites from New Jersey was that of Say (1820) who described his Baculites ovatus from what is now known as the Navesink Formation. Rocks now assigned to the Merchantville Formation yielded ammonites described as Ammonites hippocrepis Dekay, 1828 and A. placenta Dekay, 1828. Morton described Scaphites cuvieri from the unit in 1829 (the species is now regarded as a synonym of Scaphites hippocrepis), Ammonites delawarensis and A. vanuxemi in 1830, and Scaphites reniformis in 1834. Morton (1841) described his Hamites annulifer from the "Ferruginous sand at the Deep-cut of the Chesapeake and Delaware Canal", but all subsequent records of the species (a Solenoceras) come from east of this locality in what is now known as the Mount Laurel Sand. He also described his Ammonoceratites conradi from the Navesink Formation at Arneytown in the same publication. There are general accounts of the Upper Cretaceous ammonite faunas of New Jersey in Whitfield (1892) and Weller (1907), and a few species are discussed in Hyatt's posthumous monograph (1903). Modern knowledge of the fauna stems from the revision of Reeside (1962). Since 1970, Cobban (1970, 1974a) and Kennedy and Cobban (1993a, 1994a, b) have systematically revised the Upper Cretaceous ammonite faunas of New Jersey and adjacent regions on the basis of new and remarkable faunas, largely collected by members of the Monmouth Amateur Paleontologists Society (MAPS), who kindly made their collections available for study.

Woodbridge Member of the Raritan Formation.

This yields the oldest marine fauna known from the Upper Cretaceous of the United States Atlantic seaboard. The fauna is dominated by bivalves and gastropods (Richards, 1943; Stephenson, 1954) which have sufficient elements in common with the Woodbine Formation of Texas to suggest a Cenomanian date. This was recently confirmed (Cobban and Kennedy, 1990) by the discovery of two ammonites at the Sayreville Fisher Brick Company clay pit, Sayreville, Middlesex County (Pl. I, figs. 16-19). A fragment of Metoicoceras bergquisti Cobban, 1983, represents a species previously known only from the lower upper Cenomanian Metoicoceras mosbyense zone of the Mesabi Range in northern Minnesota. A second fragment of the genus Metengonoceras, represents a genus known from both middle and upper Cenomanian of the Gulf Coast.

Magothy Formation

Weller (1907, p. 34) recorded Placenticeras placenta (Dekay, 1828) and Baculites sp. from the Magothy Formation in north-central New Jersey, and Sohl and Mello (1970, p. 34) recorded Baculites asper Morton, 1833. We have not seen these specimens.

Merchantville Formation

The ammonite fauna of this unit was revised by Kennedy and Cobban (1993a), who recognized the probable presence of two assemblages. Subsequent collecting by Johnson has revealed a third assemblage. What is believed to be the oldest fauna is represented by single specimens of Submortoniceras uddeni Young, 1963, and Pseudoschloenbachia cf. P. chispaensis Adkins, 1929, Gulf Coast species that indicate the lowest Campanian zone of Submortoniceras tequesquitense of Young (1963). These were collected by L.W. Stephenson in 1932 from spoil banks along the Chesapeake and Delaware Canal, and are preserved in pale-brown phosphate, quite distinct from the preservation of the other elements of the fauna.

The bulk of the Merchantville fauna (Pl. I, figs 1-7, 10-14; Pl. II, figs 1-16) occurs as medium to dark-grayish brown molds, sometimes with iridescent nacreous shell, in sideritic concretions from localities such as Oschwald's clay pits at Cliffwood, New Jersey; the Old Graham brickyard (now Industrial Park) in Burlington County, New Jersey; and the Chesapeake and Delaware Canal. The fauna is: Pachydiscus (Pachydiscus) sp., Placenticeras placenta (Dekay, 1828), Texanites (Texanites) sp., Menabites (Delawarella) delawarensis (Morton, 1830), M. (D.) vanuxemi (Morton, 1830), Menabites (Bererella) sp., Submortoniceras punctatum (Collignon, 1948), S. uddeni Young, 1963, Cryptotexanites paedomorphicus Kennedy and Cobban 1993a (known only from the Merchantville), Glyptoxoceras sp., Chesapeakella nodatum Kennedy and Cobban, 1993a (known only from the Chesapeake and Delaware Canal), Baculites haresi Reeside, 1927, and Scaphites (Scaphites) hippocrepis (Dekay, 1828) form III of Cobban 1969. Scaphites hippocrepis III provides a precise dating for the fauna and enables correlation with the lower Campanian zone of that name in the Western Interior, the fauna of the Roxton Limestone Member of the Gober Chalk in Lamar County, Texas, (Kennedy and Cobban, 1992), and the lower Campanian of

Western Europe (Ernst and Schmid 1975, Kennedy 1986). Other elements of the fauna (*S. punctatum*) occur as far afield as Madagascar.

The third, recently discovered fauna comes from near Hedding, Burlington County, New Jersey. It includes *Placenticeras placenta* (Dekay, 1828), *Menabites* (*Bererella*) *walnutensis* Young, 1963 (Pl. I, figs 8, 9), *Glyptoxoceras aquisgranense* (Schlüter, 1872) (Pl. I, fig. 15), *Baculites* sp. nov., and a form of *Scaphites hippocrepis* III. *Menabites* (*B.*) *walnutensis* was previously known only from the holotype that was collected as float from the Austin Chalk in Austin, Texas. The *Baculites* sp. nov. corresponds to the *Baculites bohemicus* Fritsch of Van der Weijden, 1943 (pl. 12, figs. 17, 18; pl. 13, fig. 5), a form widespread in the Aachen-Vaals region of Germany, Belgium and The Netherlands, where it occurs associated with *Scaphites* (*S.*) *hippocrepis* III and passage forms to *S. hippocrepis* II.

Woodbury Formation

Placenticeras placenta is abundant in the Woodbury, which also yields *Scaphites* (*S.*) *hippocrepis* and *Baculites* sp.

Marshalltown Formation

The only ammonites known to us from the Marshalltown Formation are *Menuites portlocki complexus* (Hall and Meek, 1856) (Pl. III, figs 2-5), *Placenticeras* sp. and *Didymoceras binodosum* (Kennedy and Cobban, 1993b) (Pl. III, figs 6, 7), species confined to the upper (but not uppermost) middle Campanian of the Western Interior (Cobban and Kennedy, 1993; Kennnedy and Cobban, 1993b). The specimens were collected along the Chesapeake and Delaware Canal.

Cobban (1970) described specimens of *Didymoceras stevensoni* (Whitfield, 1877), *Didymoceras nebrascense* (Meek and Hayden, 1856) and *Exiteloceras jenneyi* (Whitfield, 1877) from the Marshalltown Formation along the Chesapeake and Delaware Canal, but subsequent work has shown these to be from the base of the Mount Laurel Sand (see below).

Wenonah Formation

The Wenonah Formation ranges from 18 m thick in the west-central part of the New Jersey Coastal Plain to as little as 5.5 m in southwestern New Jersey. The ammonite fauna was revised by Reeside (1962), Cobban (1973), and Kennedy and Cobban (1994a). The latter demonstrated that the fauna is Campanian in ammonite terms (and well below the top of the stage), although some microfossil workers (e.g., Brouwers and Hazel 1978) draw the Campanian - Maastrichtian boundary in microfossil terms within the unit. The ammonite fauna (Pl. IV, figs 1-22) (Kennedy and Cobban 1994a) is: Menuites portlocki (Sharpe, 1855) complexus (Hall and Meek, 1856), Placenticeras placenta (Dekay, 1828), P. minor Kennedy and Cobban, 1994a, Nostoceras (N.) aff. N. (N.) colubriformis Stephenson, 1941, Nostoceras (N.) puzosiforme Kennedy and Cobban, 1994a, Didymoceras binodosum (Kennedy and Cobban, 1993b), Didymoceras spp. indet., Parasolenoceras sp., Baculites texanus Cobban and Kennedy, 1995 (= Baculites scotti noded variant of Cobban, 1958, p. 662, pl. 90, figs 5-9, text-fig. 1c-e), Baculites sp., and Trachyscaphites pulcherrimus (Roemer, 1841). Didymoceras binodosum, Baculites texanus, and T. pulcherrimus occur in the Kimbro nodule zone 12-18 m below the top of the Bergstrom Formation in Travis County, Texas (Cobban and Kennedy, 1995) allowing correlation with the Gulf Coast succession. Didymoceras binodosum and B.texanus are restricted to the upper middle Campanian Baculites scotti zone of the Western Interior. T. pulcherrimus and D. binodosum occur in Europe, where they are regarded as upper Campanian, co-occurring with Bostrychoceras polyplocum.

Mount Laurel Sand

The Mount Laurel Sand is regarded as Maastrichtian by microplaeontologists, but is Campanian in ammonite terms. The known ammonite faunas all come from along the Chesapeake and Delaware Canal, including the classic locality at Biggs Farm.

The phosphates at the base of the Mount Laurel Sand include Pachydiscus (Pachydiscus) sp., Nostoceras (Nostoceras) monotuberculatum Kennedy and Cobban, 1993b, N. (N.) sp., Didymoceras platycostatum (Kennedy and Cobban, 1993c), D. stevensoni and Exiteloceras jenneyi (late subspecies) (Pl. III, figs 1, 8-19). The last two were formerly regarded as being from the underlying Marshalltown Formation (Cobban, 1970); D. stevensoni and E. jenneyi are index species of lower upper Campanian zones in the Western Interior, and indicate the extent of condensation present in the phosphatic horizon at the base of the Mount Laurel. Nostoceras (N.) monotuberculatum provides a link to the Gulf Coast sequence, and was originally described from the condensed phosphate bed at the base of the Annona Chalk near Yancy, Hempstead County, Arkansas. A single specimen is known from the basal upper Campanian Didymoceras stevensoni zone in Colorado, and three specimens are known from the Campanian zone of Didymoceras nebrascense in South Dakota.

The fauna from Biggs Farm, higher in the Mount Laurel Sand, is also phosphatized. Hundreds of individuals are known; the fauna (Pl. V, figs 1-30) (Kennedy and Cobban 1994b) is: Pachydiscus (Pachydiscus) sp., Placenticeras cf. placenta (Dekay, 1828), Placenticeras n. sp., Sphenodiscus sp., Didymoceras draconis (Stephenson, 1941), D. cheyennense (Meek and Hayden, 1856). Anaklinoceras reflexum Stephenson, 1941, A. tenuicostatum Kennedy and Cobban 1994b, Oxybeloceras meekanum (Whitfield, 1877), Solenoceras annulifer Morton, 1842, Baculites ovatus Say, 1820, B. undatus Stephenson, 1941, Hoploscaphites vistulensis Blaszkiecwicz, 1980, Jeletzkytes compressus (Roemer, 1841). The last two scaphites occur in Western Europe; their ranges are somewhat imprecisely defined within the upper but not uppermost Campanian; Didymoceras draconis occurs in the upper Campanian of Calabria, Italy, where it was recently described as Nostoceras hyatti (Pallini and Giudici, 1994). Norm Brown (Lakeside, California) has recently shown us specimens from Baja (Mexico), and from the San Diego area, California. The species was originally described from the Neylandville Marl near Corsicana, Texas. Anaklinoceras reflexum, originally described from the Neylandville Marl of Texas, also provides a link to the Gulf Coast sequence, and is known from Israel (Lewy, 1986).

Correlation with the Western Interior shows the Biggs Farm fauna to be equivalent to the upper Campanian Didymoceras cheyennense zone (on the basis of the common occurrence of the index species), plus the Baculites compressus zone, which has yielded A. reflexum in Colorado (Cobban, Kennedy, and Scott, 1992).

Navesink Formation

The Navesink Formation yields rich faunas that are both upper Campanian and Maastrichtian in ammonite terms (Pl. VI, figs 1-17; Pl. VII, figs 1-3, 7-10). Cobban (1974a) described the faunas from Atlantic Highlands, New Jersey, and subsequent collecting from here and elsewhere reveals a complex story. Most of the ammonites known to us are phosphatized and most come from condensed nodule beds near the base of the unit.

At Atlantic Highlands, phosphatic ammonites occur at two horizons (Mendryk, in Cobban, 1974a, p.1). A lower layer, 15-20 cm thick and 0.7 m above the base of the Navesink, yields Pseudophyllites indra (Forbes, 1846), Kitchinites sp., Baculites ovatus Say, 1820, Baculites claviformis Stephenson, 1941, Nostoceras (N.) helicinum (Shumard, 1861), N. (N.) hyatti Stephenson, 1941, N. (N.) pauper (Whitfield, 1892), N. (N.) approximans (Conrad, 1855), Axonoceras cf. A. angolanum Haas, 1942, Lewyites oronensis (Lewy, 1969), Cirroceras conradi (Morton, 1841), Hoploscaphites pumilus (Stephenson, 1941), Jeletzkytes nodosus (Owen, 1852) and Jeletzkytes sp. This fauna defines an upper Campanian Nostoceras (N.) hyatti zone (Kennedy and Cobban, 1993d). Subsequent collecting has produced Pachydiscus (P.) neubergicus neubergicus (Hauer, 1858) (Pl. VI, figs 16, 17) and Nostoceras (N.) alternatum (Tuomey, 1854) at this level, indicating some admixture of lower Maastrichtian material. A second layer, 0.2 m above the first and 0.12 m thick, yields far fewer ammonites, including Pachydiscus (Pachydiscus) neubergicus neubergicus (Hauer, 1858), Nostoceras (N.) mendryki Cobban, 1974a, Jeletzkytes sp., and Baculites. This is a lower Maastrichtian assemblage.

The only ammonites from higher in the sequence that are known to us are a Maastrichtian Eubaculites cf. labyrinthicus (Morton, 1834) from Crosswicks Creek, south of Walnford in Monmouth County; an unphosphatized Jeletzkytes criptonodosus Riccardi, 1983, from the middle of the Navesink near Middletown, Monmouth County; and a Discoscaphites conradi (Morton, 1834), from spoil heaps at the Inversand Pit, Sewell, Gloucester County.

The older, Nostoceras hyatti zone fauna of the Navesink Formation can be directly correlated with the highest European Campanian, the Nostoceras pozaryskii zone of Blaszkiewicz (1980), and the higher part of the Belemnella langei zone of authors. This is based upon the recognition that the types of N. (N.) pozaryskii are specimens of both N. (N.) hyatti and N. (N.) helicinum, while Acanthoscaphites praequadrispinosus Blaszkiewicz, 1980, which is restricted to the zone, is a synonym of Jeletzkytes nodosus. The pozaryskii zone should be renamed the N. (N.) hyatti zone in our view.

The younger Navesink fauna at Atlantic Highlands correlates with the Belemnella lanceolata zone of the European lower Maastrichtian on the basis of the occurrence of P. (P.)

neubergicus in both, plus the close similarity between N. (N.) mendryki and N. (N.) schloenbachi (Favre, 1869), as already pointed out by Cobban (1974a).

The N. (N.) hyatti zone can be widely recognized in the Gulf Coast, and faunas are described fully elsewhere (Kennedy and Cobban, 1993d; Cobban and Kennedy, 1994). The Saratoga Chalk of Arkansas yields 17 species: Gaudryceras sp. (rare), Pachydiscus (Pachydiscus) arkansanus (Stephenson, 1941) (rare), Pseudokossmaticeras galicianum (Favre, 1869) (rare), Nostoceras (Nostoceras) approximans (common), N. (N.) helicinum (common), N. (N.) hyatti (common), N. (N.) pauper (uncommon), N. (N.) colubriformis Stephenson, 1941 (rare), N. (N.) sp. nov. (rare), Didymoceras draconis (Stephenson, 1941) (rare), Cirroceras conradi (uncommon), Lewyites oronensis (uncommon), Solenoceras cf. texanum (Shumard, 1861) (rare), Baculites undatus (rare), B. ovatus (abundant), Hoploscaphites pumilus (uncommon), and Jeletzkytes nodosus (rare).

In Tennessee the zone is represented in the Coon Creek Tongue of the Ripley Formation at its type locality, which yields N. (N.) hyatti, N. (N.) approximans, C. conradi, Parasolenoceras sp., Solenoceras sp., Baculites claviformis, and J. nodosus.

In northeast Texas, there is an excellent representation at several localities in the Nacatoch Sand. USGS Mesozoic locality 17368 (near Corsicana, Navarro County) is low in the Nacatoch, with N. (N.) hyatti?, N. (N.) colubriformis (Stephenson, 1941), Solenoceras multicostatum Stephenson, 1941, and S. texanum. Higher is USGS Mesozoic locality 518 (bank of Postoak Creek at north edge of Corsicana, Navarro County) with N. (N.) hyatti, N. (N.) helicinum, S. multicostatum and Baculites undatus. High in the Nacatoch is USGS Mesozoic locality 762 (near Chatfield, fossiliferous concretions in village and fields and ravines, Navarro County), with Pachydiscus (P.) arkansanus, N. (N.) helicinum, N. (N.) approximans, N. (N.) splendidum, C. conradi, S. multicostatum, S. texanum, B. undatus, S. pumilus and J. nodosus.

The younger fauna of the Navesink at Atlantic Highlands is in part or total to be correlated with the Maastrichtian N. (N.) alternatum zone (Cobban, 1974b), represented in the Coon Creek Tongue of the Ripley Formation in northeastern Mississippi and localities in equivalent parts of the Ripley Formation in Alabama and Georgia as well as the Nacatoch Sand in southwestern Arkansas. Rare phosphatized fragments of the index species occur in the Prairie Bluff Chalk in Alabama.

Eubaculites labyrinthicus is Maastrichtian and also present in the Prairie Bluff Chalk in Alabama; Jeletzkytes criptonodosus occurs in the Prairie Bluff Chalk in Alabama and in the Ripley Formation in Union County, Mississippi.

Discoscaphites conradi occurs some way above the base of the Maastrichtian in the Severn Formation in Maryland, the Prairie Bluff Chalk in Mississippi, and the Corsicana Formation (Kemp Clay) in Texas (Kennedy and Cobban, 1993e; Landman and Waage, 1993).

Several elements of the Navesink faunas occur in the Western Interior, and confirm the wide time span represented in the sequence:

Jeletzkytes nodosus: B. compressus, B. cuneatus, B. reesidei and B. jenseni zones
Cirroceras conradi: B. cuneatus and B. reesidei zones.
Lewyites oronensis: B. cuneatus and B. reesidei zones
Nostoceras (N.) hyatti: B. jenseni zone
Nostoceras (N.) approximans: B. jenseni zone
Jeletzkytes criptonodosus: B. baculus, B. grandis zones
Discoscaphites conradi: Hoploscaphites nicolletti and Jeletzkytes nebrascensis zones

Red Bank Sand and Tinton Sand

The only ammonites we have seen from these units are specimens of Sphenodiscus lobatus (Tuomey, 1854) (= Sphenodiscus lenticularis (Owen, 1852) of authors; Ammonites lenticularis of Owen is a homonym of Ammonites lenticularis Phillips, 1829). This species has a very wide geographic distribution outside New Jersey: the Severn Formation in Maryland, the Peedee Formation in North Carolina, Providence Sand in the Chatahoochee River area of eastern Alabama, upper part of the Ripley Formation in Mississippi, Prairie Bluff Chalk in Alabama and Mississippi, Corsicana Formation in northeast Texas, Escondido Formation in Trans-Pecos Texas and northern Mexico, and the Pierre Shale and Fox Hills Formation in the Western Interior. It ranges throughout all but the lower parts of the Maastrichtian in the Gulf Coast region, where the oldest well-dated occurrences are in association with S. pleurisepta (Conrad, 1857) and Discoscaphites iris (Conrad, 1858) in the Owl Creek Formation of

Mississippi, Tennesee, and Missouri (Stephenson, 1955). In the Western Interior it ranges from the Hoploscaphites nicolletti zone to the Jeletzkytes nebrascensis zone. Landman and Waage (1993, p. 17) record Sphenodiscus ?lenticularis from the slightly older Hoploscaphites birkelundi zone. Sphenodiscus lobatus is also known from the Maastrichtian of Israel and Nigeria (Zaborski, 1982).

Ammonites from the basal Paleocene

Maastrichtian ammonites occur in the basal Paleocene Hornerstown Formation at a number of localities in New Jersey (Pl. VII, figs 4-6, 11-15). They represent Maastrichtian material reworked into Paleocene matrix by physical and biological processes. They include Sphenodiscus lobatus, Pachydiscus (Neodesmoceras) sp., and Baculites sp. from the Inversand marl pit in Gloucester County, and Baculites sp. from Crosswick Creek southwest of Arnytown, Monmouth County. The U.S. National Museum of Natural History has three well preserved specimens of Eubaculites carinatus (Morton, 1834) from the J.B. Marcou Collection in a preservation suggesting derivation from the basal Hornerstown.

Repositories of figured specimens:

NJM:	New Jersey State Museum, Trenton, New Jersey
MAPS:	Monmouth Amateur Paleontologists Society, West Long Branch, New Jersey.
USNM:	U.S. National Museum of Natural History, Washington, D. C.

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Figure 1. Correlation of the Campanian-Maastrichtian succession in New Jersey with the Western Interior ammonite zonation.

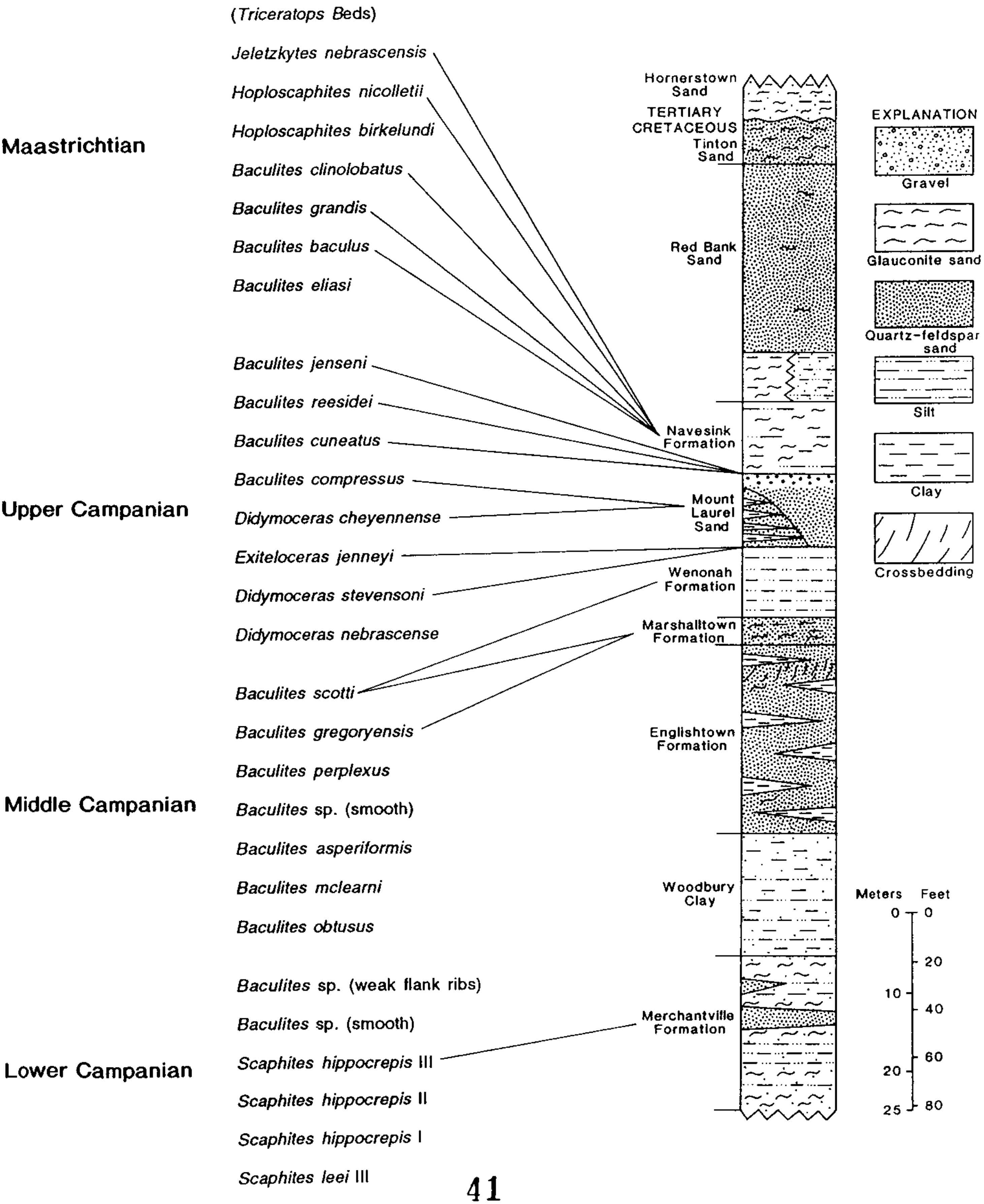

PLATE I

Ammonites from the Woodbridge Member of the Raritan Formation and the Merchantville Formation.

Figs 1, 2, 13, 14. Texanites (Texanites) sp. USNM 445209, Merchantville Formation, Chesapeake and Delaware Canal.

Figs 3-7. Scaphites (Scaphites) hippocrepis (Dekay 1828) form III of Cobban, 1969, from the Merchantville Formation. 3, 4, microconch, USNM 445252, Oschwald's clay pit, Monmouth County; 5-7, macroconch, USNM 445255, Old Graham Brick Company pits, Maple Shade, Burlington County.

Figs 8, 9. Menabites (Bererella) walnutensis Young, 1963. MAPS Collection, Merchantville Formation, near Hedding, Burlington County.

Figs 10-12. Chesapeakella nodatum Kennedy and Cobban, 1993a. USNM 445237, Merchantville Formation, Chesapeake and Delaware Canal.

Fig. 15. Glyptoxoceras aquisgranense (Schlüter, 1872). MAPS Collection, from the Merchantville Formation near Hedding, Burlington County.

Figs 16, 17. Metoicoceras bergquisti Cobban, 1983. USNM 445088, Woodbridge Clay Member of Raritan Formation, Sayreville-Fisher Brick Company pit at Sayreville, Middlesex County.

Figs 18, 19. Metengonoceras sp. USNM 445809, Woodbridge Member of Raritan Clay Formation, Sayreville-Fisher Brick Company Pit at Sayreville, Middlesex County.

All figures are x 1.


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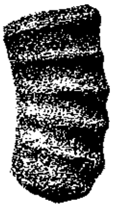
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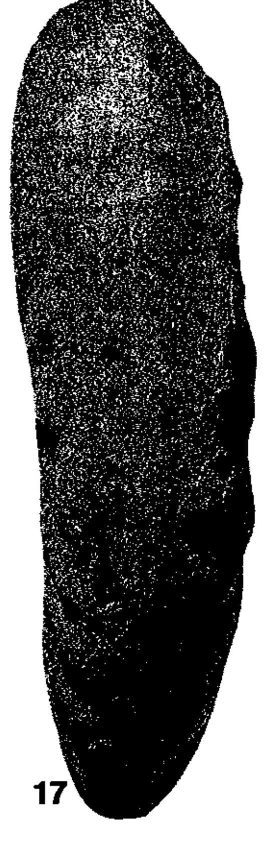
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PLATE II

Ammonites from the Merchantville Formation

Figs 1, 2. Placenticeras syrtale (Morton, 1834). USNM 445204, Chesapeake and Delaware Canal.

Figs 3-5. Baculites haresi Reeside, 1927. USNM 442541, from the old Graham Company Brick Pits, Maple Shade, Burlington County.

Figs 6, 7. Submortoniceras punctatum Collignon, 1948: USNM 445226, Chesapeake and Delaware Canal.

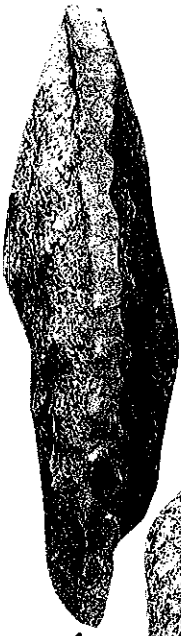
Figs 8-10. Cryptotexanites paedomorphicus Kennedy and Cobban, 1993a. Holotype, USNM 445231, Chesapeake and Delaware Canal.

Figs 11, 12. Placenticeras placenta (Dekay, 1828). USNM 445206, Chesapeake and Delaware Canal.

Figs 13, 14. Menabites (Delawarella) delawarensis (Morton, 1830). USNM 445217, Chesapeake and Delaware Canal.

Figs 15, 16. Menabites (Delawarella) vanuxemi (Morton, 1830). USNM 445221, from the old Graham Company Brick Pits, Maple Shade, Burlington County.

All figures are x 1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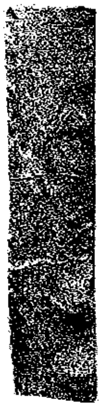
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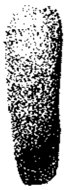
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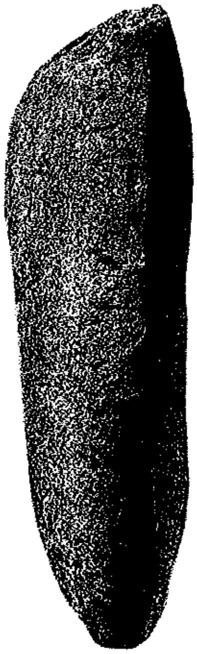
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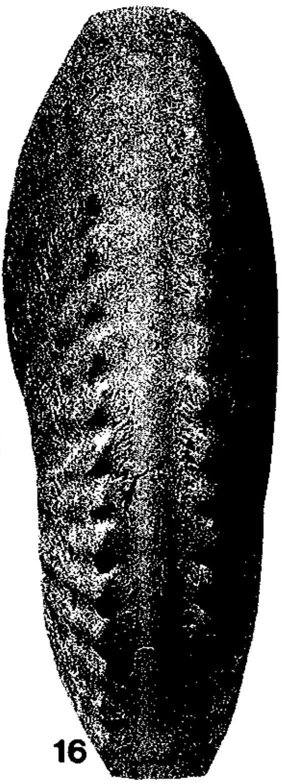
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PLATE III

Ammonites from the Marshalltown Formation and the base of the Mount Laurel Sand along the Chesapeake and Delaware Canal.

Figs 1, 8, 9. *Nostoceras (Nostoceras) monotuberculatum* Kennedy and Cobban, 1993b. 1, MAPS 2038a; 8, 9, USNM 445407, from the base of the Mount Laurel Sand.

Figs 2-5. *Menuites portlocki* (Sharpe, 1855) *complexus* (Hall and Meek, 1856). 2, 3, USNM 445410; 4, 5, USNM 445405, both from the Marshalltown Formation.

Figs 6, 7. *Didymoceras binodosum* (Kennedy and Cobban, 1993b), MAPS A2022b, from the Marshalltown Formation.

Figs 10, 11. *Didymoceras platycostatum* (Kennedy and Cobban, 1993c). USNM 445412, from the base of the Mount Laurel Sand.

Figs 12, 13, 18, 19. *Didymoceras stevensoni* (Whitfield, 1877). 12, 13, MAPS Collection; 18, 19, USNM 445414, from the base of the Mount Laurel.

Figs 14-17. *Exiteloceras jenneyi* (Whitfield, 1877) (subspecies). MAPS Collection; from the base of the Mount Laurel Sand.

All figures are x 1.


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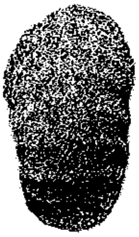
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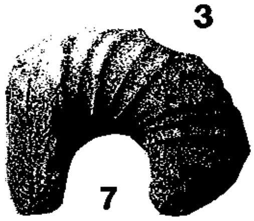
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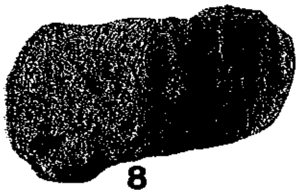
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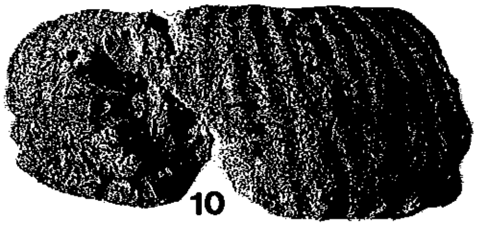
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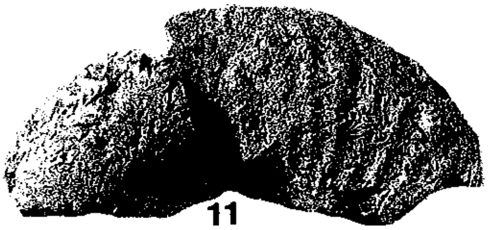
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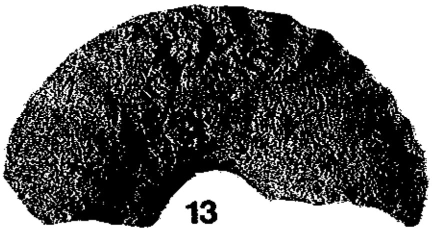
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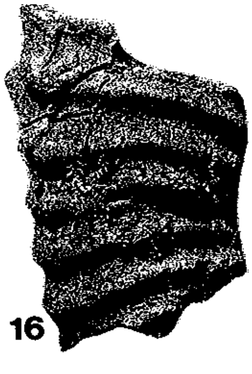
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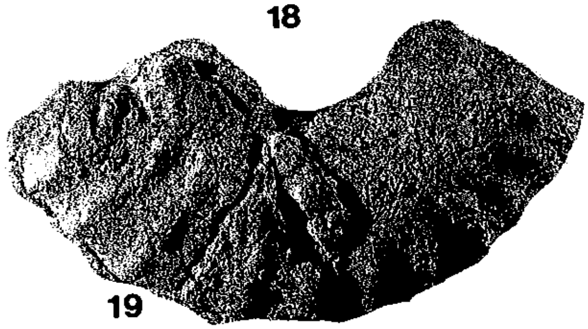
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PLATE IV

Ammonites from the Wenonah Formation of Monmouth County.

Figs 1-4, 11. Didymoceras binodosum (Kennedy and Cobban, 1993b). 1-3, USNM 445718, east bank of Hop Brook, just south of Route 520, east of Holmdel; 4, USNM 445186, from tributary to Big Brook, near Marlboro; 11, USNM 445190, Big Brook, east of Marlboro.

Fig. 5. Nostoceras (Nostoceras) puzosiforme Kennedy and Cobban, 1994a. Holotype, USNM 445177.

Figs 6, 7, 9, 10. Trachyscaphites pulcherrimus (Roemer, 1841). 6, 7, USNM 187708, from Big Brook 2.9 km east of Marlboro; 9, 10, private collection J. Brzostoski, tributary to Big Brook 1.6 km east of Marlboro.

Fig 8. Nostoceras (Nostoceras) aff. N. (N.) colubriformis Stephenson, 1941. Latex cast, USNM 44517, tributary to Big Brook, near Marlboro.

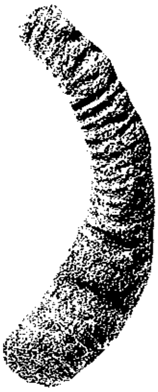
Figs 12, 13, 17, 18. Menuites portlocki (Sharpe, 1855) complexus (Hall and Meek, 1856). 12, 13, USNM 445159; 17, 18, USNM 445165, from Big Brook just west of Hillsdale road and 2.9 km east of Marlboro.

Figs 15, 16. Baculites texanus Cobban and Kennedy, 1995. USNM 445188, Big Brook just west of Hillsdale Road and 2.9 km east of Marlboro.

Figs 19, 20. Placenticeras minor Kennedy and Cobban, 1994a. USNM 445173, from Hop Brook, 1.3 km east-northeast of Holmdel.

Figs 21, 22. Placenticeras placenta (Dekay, 1828). USNM 445163, from east flowing tributary of Willow Creek 1.4 km east of Hillsdale.

All figures are x 1.



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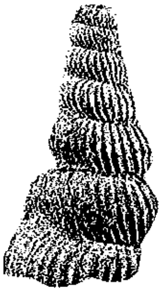

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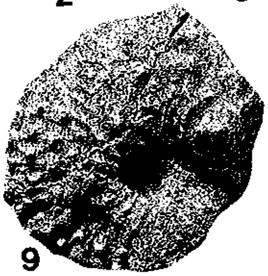

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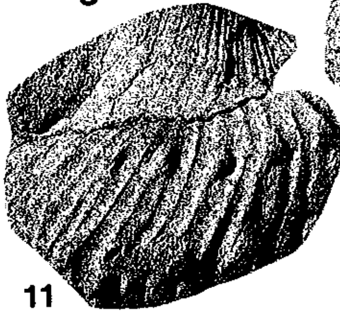

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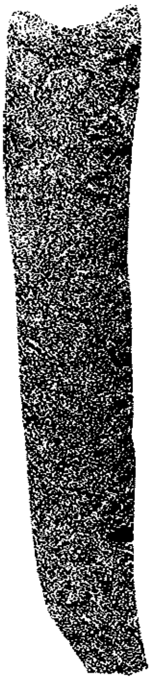

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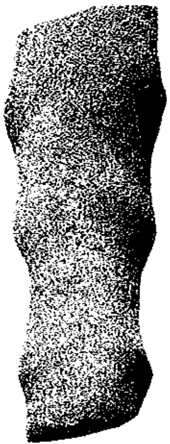

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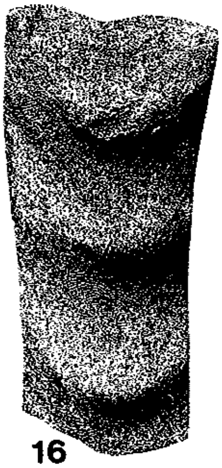

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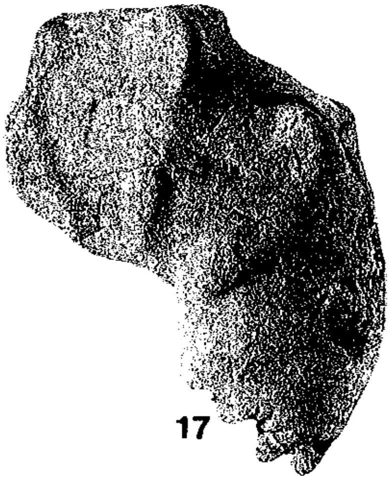

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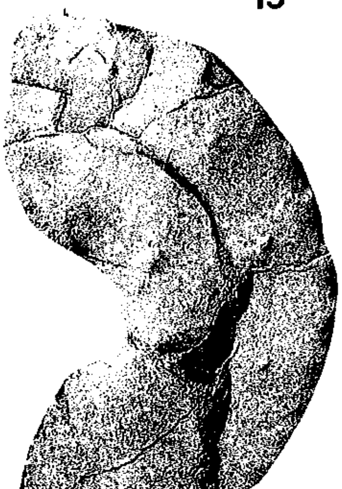

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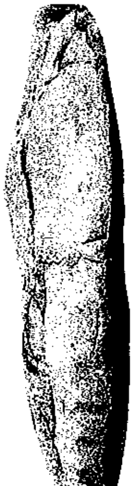

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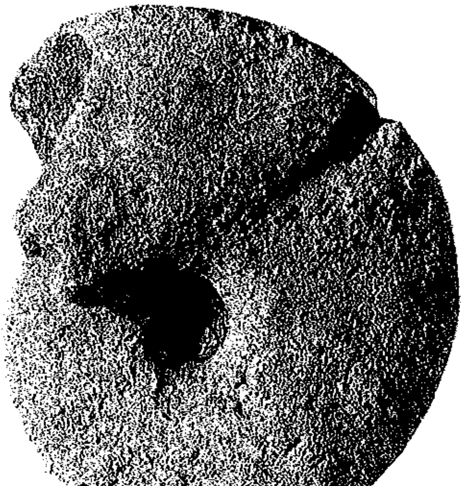

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Plate V

Ammonites from the Mount Laurel Sand at Biggs Farm on the Chesapeake and Delaware Canal.

Figs 1-3, 11-14, 20, 21. Didymoceras cheyennense (Meek and Hayden, 1856). 1-3, USNM 445105; 11-14, USNM 445106; 20, 21, USNM 445104.

Figs 4-7. Anaklinoceras tenuicostatum Kennedy and Cobban, 1994b. USNM 445108.

Figs 8-10. Anaklinoceras reflexum Stephenson, 1941. USNM 445114.

Figs 15, 16. Oxybeloceras meekanum (Whitfield, 1877). USNM 445117.

Figs 17-19. Solenoceras annulifer Morton, 1842. USNM 445124.

Figs 22, 23. Baculites undatus Stephenson, 1941. USNM 445139.

Figs 24, 25. Baculites ovatus Say, 1820. USNM 445137.

Figs 26, 27. Hoploscaphites vistulensis Blaskiewicz, 1980. USNM 445141.

Figs 28, 29. Jeletzkytes compressus (Roemer, 1841). MAPS A20206.

Figure 30. Nostoceras (Nostoceras) draconis Stephenson, 1941. USNM 445094.

Figures 1-16, 22-30 are x 1; figures 17-19 are x 2.


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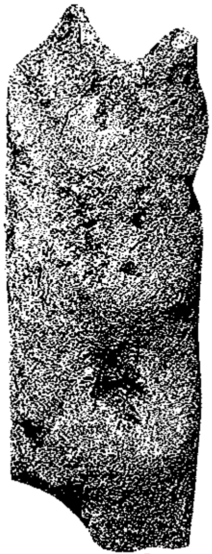
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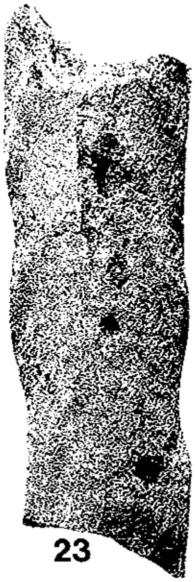
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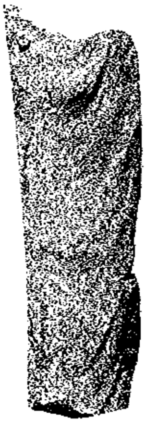
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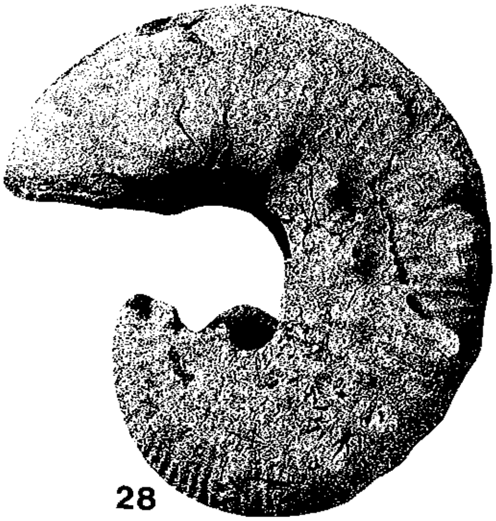
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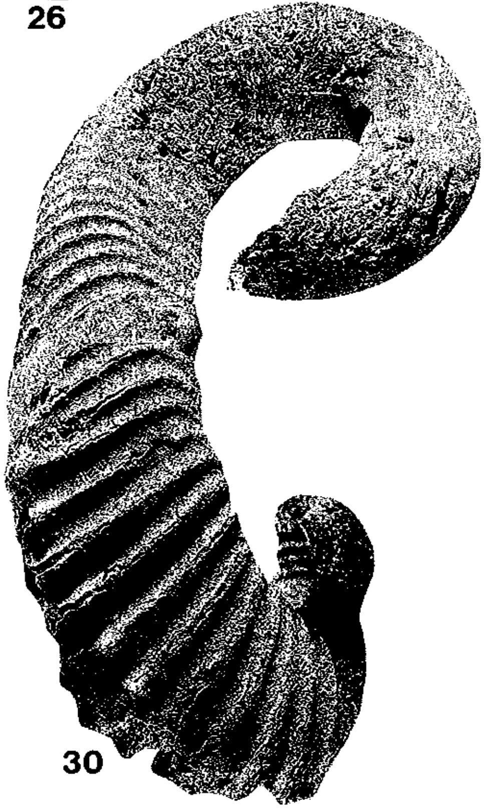
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Plate VI

Ammonites from the base of the Navesink Formation at Atlantic Highlands.

Figs 1, 2. *Hoploscaphites pumilus* (Stephenson, 1941). MAPS Collection.

Fig. 3. *Jeletzkytes nodosus* (Owen, 1852). MAPS A2020a.

Figs 4, 5. *Pseudophyllites indra* (Forbes, 1846). USNM 445418.

Fig. 6 *Nostoceras (Nostoceras) mendryki* Cobban, 1974a. MAPS A2030a.

Figs 7-8. *Nostoceras (Nostoceras) hyatti* Stephenson, 1941. 6, MAPS Collection; 7, 8, macroconch, MAPS Collection.

Figs 9-12. *Nostoceras (Nostoceras) approximans* (Conrad, 1855). 9, 10, microconch, MAPS Collection; 11, 12, macroconch, MAPS Collection.

Figs 13-15. *Baculites ovatus* Say, 1820. MAPS Collection.

Figs 16, 17. *Pachydiscus (Pachydiscus) neubergicus* (Hauer, 1858). MAPS A26545a.

All figures are x 1.


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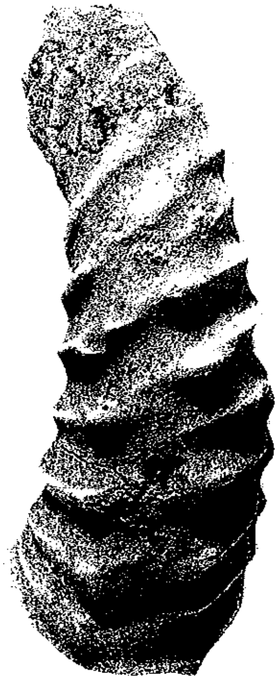
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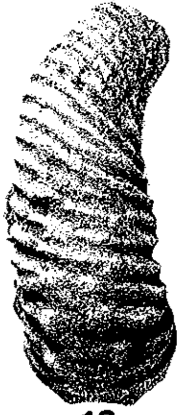
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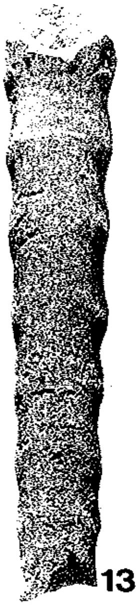
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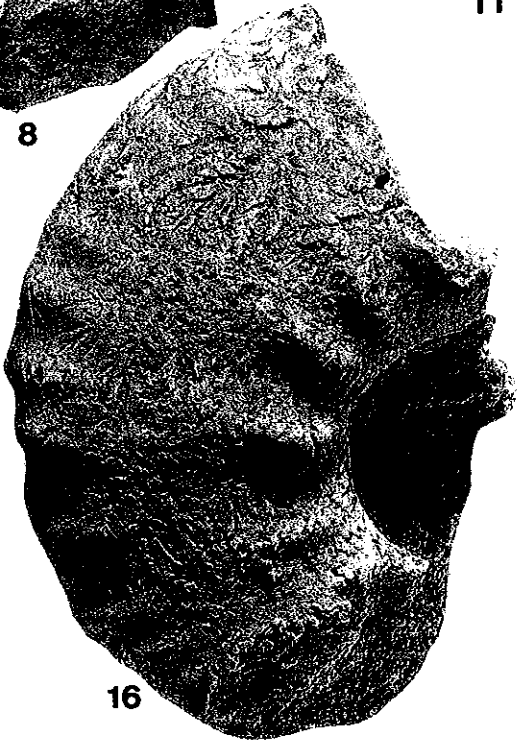
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Plate VII

Ammonites from the base of the Navesink Formation and the base of the Hornerstown Formation.

Figs 1-3. Nostoceras (Nostoceras) helicinum (Shumard, 1861). MAPS A2027. Base of Navesink Formation, Atlantic Highlands.

Figs 4-6. Eubaculites carinatus (Morton, 1834). USNM 12691, ex J.B. Marcou Collection, labelled 'New Jersey' and by their preservation from the base of the Hornerstown Formation.

Figs 7, 8. Nostoceras (Nostoceras) mendryki (Cobban, 1974). MAPS A2030a, base of Navesink Formation, Atlantic Highlands.

Figs 9, 10. Nostoceras (Nostoceras) hyatti Stephenson, 1941. MAPS A2004a, base of Navesink Formation, Atlantic Highlands.

Figs 11, 12, 14, 15. Pachydiscus (Neodesmoceras) sp. 11, 12, NJM11284e; 14, 15, NJM11284a base of Hornerstown Formation, Inversand pit, Sewell, Gloucester County.

Fig. 13. Sphenodiscus lobatus (Tuomey, 1854). NJM11328o, base of Hornerstown Formation, Inversand Pit, Sewell, Gloucester County.

All figures are x 1.


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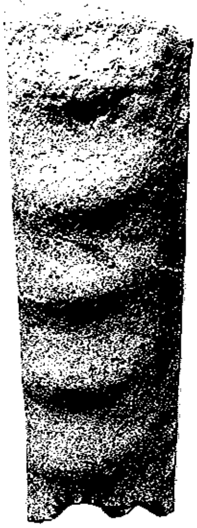
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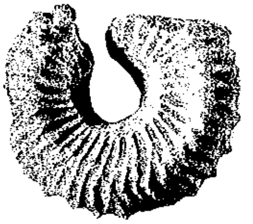
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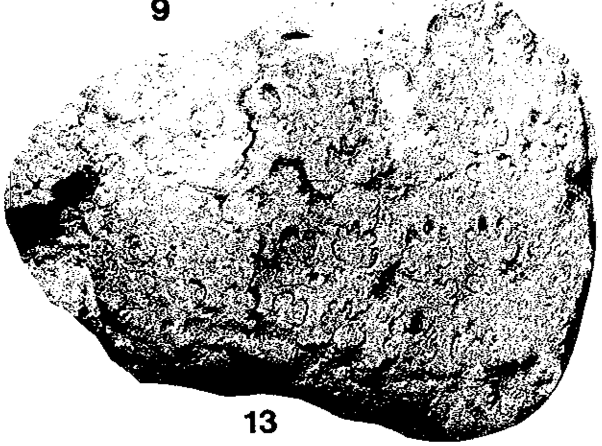
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Collapse of the Cretaceous Marine Community and Recovery of Paleocene Biota in the K/T Sequence of New Jersey

by William B. Gallagher
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Trenton, NJ 08625-0530

Abstract- Patterns of differential extinction and survival in the Late Cretaceous-early Tertiary sequence of New Jersey indicate that marine invertebrates with planktotrophic larval stages suffered reduction in stocks, while the marine communities of Danian time were dominated by invertebrates with non-planktotrophic reproductive strategies. Among vertebrates, duraphagous predators and apical predators were affected by the K/T event, leaving predatory niches open which were filled by other types of organisms in the Danian. Diversity rebound occurs in the Thanetian with the establishment of the Vincenttown limesand patch reef community.

Introduction

The turn-over in both phytoplankton and zooplankton at the Cretaceous/Tertiary boundary is a well-recognized aspect of the K/T mass extinction event that has fueled a vigorous debate over the rates and causes of the terminal Mesozoic biotic crisis. On the one side, traditional gradualist interpretations see a protracted dwindling of Cretaceous plankton stocks, albeit a geologically rapid dwindling. The other side of the debate interprets the pattern of extincton as catastrophic and very rapid, the result of an asteroid impact and its consequent environmental disruption. Part of the debate has centered on how complete some K/T sections are, in terms of continuous sedimentary record across the boundary (Macleod and Keller, 1991). Some sections are of course more complete than others, and many sections show greater or lesser amounts of latest Cretaceous time missing. The widespread Cretaceous/Tertiary missing interval may be due to the cause of the mass extinction itself, but in sections that are missing some latest Cretaceous or earliest Danian sediments, the missing interval is not particularly important with respect to determining the larger-scale patterns of macroevolutionary and paleoecological changes across a major geological datum. The broad-brush picture of extinction and survival is actually at the center of interest in mass extinction studies, and can be determined with some certainty even in Maastrichtian-Danian sections that are not perfectly complete.

Cretaceous Marine Communities

The abundant, diverse Cretaceous plankton populations supported a fecund marine community in the northern Atlantic coastal plain region in Campanian and Maastrichtian times. The most conspicuous mega-invertebrates are the large oysters that form dense well-defined concentrations in several of the Late Cretaceous formations. Numerically, genera like Exogyra and Pycnodonte are the dominant benthos in this interval. In the water column above, the ammonites were an important part of the nektonic community. Evolving rapidly into a diversity of forms, they are important biostratigraphic fossils that allow us to correlate these deposits more widely. Both the oysters and the ammonites shared an intersting feature of their life-cycle; they were planktotrophic, spending their larval stages developing in the plankton and utilizing planktonic food resources before assuming adult form (Gallagher, 1991; Scheltema, 1977; Shigeta, 1993). The adult mollusks were in turn consumed by a variety of duraphagous predators, such as sharks, rays, teleost fish, turtles, and mosasaurs (Gallagher, 1993). This food web depended upon abundant planktonic food resources; moroeover, the planktonic larval stages of planktotrophic mollusks were an important part of the planktonic trophic supplies themselves. Any detrimental influence on the plankton would have had a negative impact on the structure of Cretaceous marine communities, whether it was sudden or gradual. In fact, the most obvious change in the marine fossil record at the K/T boundary is the disappearance of the large dense oyster community and the nektonic ammonites. Concomitantly, numerous Cretaceous duraphagous predators disappeared (Gallagher, 1993).

Paleocene Marine Communities

The disappearances are particularly striking in the Danian fossil communities, which are dominated by sponges, corals and brachiopods. In the Upper Hornerstown Formation, these minimalist organisms are numerically the most common mega-invertebrates (Gallagher, 1991). They represent a Paleozoic fauna that originated in a pre-Mesozoic marine realm devoid of the rich planktonic food resources of the Cretaceous. All three kinds of benthos do not depend upon a planktotrophic larval stage. Sponges are capable of budding; corals undergo alternation of generation and can also reproduce asexually; and brachiopods are lecithotrophic, depending upon yolk-rich eggs for reproduction. Among the cephalopods, while planktotrophic ammonites became extinct, their egg-laying relatives, the nautilids, survived in the form of Eutrophoceras dekayii. Oysters and other bivalves are present in the Danian deposits, but they are dwarfed forms that are not nearly as common as brachiopods. This is an interesting, if brief, reversal of the post-Paleozoic pattern of bivalve dominance among the shelled benthos. In the oligotrophic ocean of the early Paleocene, those organisms which did not have a planktotrophic developmental stage were at an advantage, at least until plankton stocks reestablished themselves (Gallagher, 1991, 1992, 1993).

This apparently occurred by the Thanetian stage, when marine diversity increased and an early post-K/T reef community formed the limesand facies of the Vincentown Formation. This deposit was mined for lime, and its distribution is spotty and limited. The limesand occurs as indurated limestone layers interbedded with calcareous sand composed largely of bryozoan fragments. The K/T mass extinction event decimated reef-building scleractinian corals as well as the principal reef-builders of the Late Cretaceous, the rudists. The Thanetian bioherms of New Jersey were mounded build-ups that were largely composed of bryozoa, but that also supported the first diverse marine community after the K/T boundary.

Among the nekton, the higher trophic levels were filled by a variety of other animals that occupied the niches left vacant by the extinction of the Cretaceous duraphagous predators and the larger apical predators like the marine reptiles. The role of large marine predator was quickly filled by the Paleocene lamnoid sharks, including the ancestors of Carcharodon, and by large marine snakes like Paleophis (Gallagher, 1993).

Conclusions

The large-scale pattern of extinction and survival within the Late Cretaceous to Early Tertiary sequence in New Jersey shows a pattern of selectivity based on reproductive strategy. Marine invertebrates with planktotrophic larval stages suffered diminution of stocks, while a variety of types with non-planktotrophic strategies briefly flourished in the Danian. The collapse of the Cretaceous marine trophic pyramid was completed by the decimation of duraphagous predators dependent upon the planktotrophic molluscs for their food resources. Diversity rebounded in the Thanetian with the appearance of limited patch-reef communities dominated by cheilostome bryozoan framework builders. With the disappearance of the large marine reptiles of the Late Cretaceous, the ecological niche of large marine predator could be filled by other organisms.

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PALEOECOLOGY OF THE LATE CRETACEOUS OYSTERS FROM NEW JERSEY AND DELAWARE

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ABSTRACT- Examination of nearly 200 and 535 left and right valves of *Exogyra cancellata* and *Pyncnodonte mutabilis* from the Mount Laurel Formation in northern Delaware revealed that 83% and 50% of the specimens have shell breakage repairs, often as many as seven scars per valve. Additionally, random distributions of clionid borings occur on the right valves of both oysters and the left valves of *P. mutabilis.* However, clionid sponge borings are concentrated on the dorsal beak area of left valves of *E. cancellata*, a valve region exposed above the sediment surface in life position. Lithophagid borings are concentrated in the dorsal-anterior region of the left valves of both oysters, again areas of the shell that would be exposed to larval recruitment. Unbored right and left valves of either species are significantly thinner than their bivalve- and sponge-bored counterparts which suggests valve-size selectivity by the *Lithophaga* and *Cliona* settling larvae, and/or ecophenotypic thickening of the hosts shell in response to parasitic bivalve and sponge infestations.

INTRODUCTION

Exogyrids and pyncnodontids are abundantly preserved in the glauconitic muddy sands of the Late Cretaceous Mount Laurel and overlying Navesink Formations in New Jersey (Richards, 1958) and the correlative Mount Laurel and underlying Marshalltown Formations of the Chesapeake and Delaware Canal area of Delaware (Lauginiger, 1988). Collections of both oyster genera where made from the Navesink Formation exposed in Poricy Brook, New Jersey (Boyd, 1982) and in spoil piles of Mount Laurel-Marshalltown sediments along a graded road flanking a drainage ditch east of U.S. 13 near St. Georges, Delaware, on the northern side of the Chesapeake & Delaware Canal (See Lauginiger, 1988, Fig. 1 for index map). The sample of *Exogyra convexa* and *Pyncnodonte (Gryphaea) convexa* from the Navesink Fromation included 196 and 85 specimens, respectively (Boyd, 1982). The larger sample size of *E. cancellata* and *P. mutabilis,* which included 198 and 554 specimens, respectively from the Mount Laurel Formation in Delaware is the primary focus of this investigation, but the observations on sublethal shell breakage and distribution of borings in to the valves can be extrapolated to the exogyrids and pyncnodontids in New Jersey.

Both *E. cancellata* and *P. mutabilis* commonly display boreholes attributable to endolithic dwellers, namely the sponge *Cliona cretacica* and the suspension-feeding clam *Lithophaga ripleyana* (Richards, 1958). In addition to these borings, both oyster species frequently show repaired predation scars in their shells which are attributable to the durophagous (shell-crushing) predators common to the Late Cretaceous sandy, muddy shallow, shelfal environments. Predators which possibly left incriminating sublethal breakage in shells of exogyrids and pyncnodontids include brachyuran crabs, ammonoids, sharks, and rays. Even lifeless models of *Exogyra* and *Gryphaea* can induce modern crabs to attack them (Labarbera, 1981). *Trypanites* -borings, probably made by lithophagids, show site selectivity in Gulf Coast Cretaceous pyncnodontids (Bottjer, 1982), but published data on the distribution of parasitic clionid and lithophagid borings, as well as sublethal predational scars, is lacking for the Mid-Atlantic Coast Cretaceous oysters. The question of species-,size-, and site-specificity on New Jersey and Delaware exogyrids versus pyncnodontids shells by durophagous predators and shell-boring parasites, namely *Cliona* and *Lithophaga*, will be addressed in this investigation.

PREDATORS AND PARASITES: DISTRIBUTIONS OF SCARS AND BORINGS

Both *Exogyra* and *Pyncnodonte* show frequent evidence of sublethal durophagous (shell crushing) attacks. The sublethal damage may be a dorsally curving fracture producing a scalloped outline to otherwise concentric growth lines (Fig. 1A & B) in either species. Alternatively, clefts, with growth lines forming a chevron shape across the recessed area, may extend from the ventral-lateral margin dorsally for two thirds the length of the shell (Fig. 1C). Occasionally the clefts and chevron-shaped growth line pattern terminate at a *Trypanites* borehole, indicating the lithophagid bore into the valve margin of a life host that subsequently sutured the breach in the accretion of the shell ventral to the infestation (Fig. 1D). More extensive sublethal breakage removed large chunks of the left valve producing an irregular, embayed, fracture outline (Fig. 1E). Similar scalloped, cleft, and embayed sublethal fracture patterns in the shells of concavo-convex, thin, strophomenid brachiopods have been described by Alexander (1986). Only 23 of 160 convex left valves of *E. cancellata* lack repairs, an indication that these oysters had a small chance of survival into adulthood without sustaining shell damage. In contrast, right valves of *E. cancellata* and *P. mutabilis* rarely show repair, possibly an indication of the inability of a clawed or jawed predator to secure a purchase on this valve.

Most damaged valves show multiple repairs (Fig. 1, A & B). As many as seven repairs are spaced from the dorsal to the ventral portions of the left valve surface of large individuals of both oyster species, indicating that no size refuge from attack occurred as the individuals lengthened and thickened their shells (Fig. 3A & B). The fact that 83% of exogyrid left valves display repairs, whereas 50% of pyncnodontids left valves show scars does not necessarily indicate that the molluscivores preferred to prey on *E. cancellata.* The frequency of successful predation, which would be difficult to reconstruct from fragmented shells, may be inversely related to unsuccessful predatory attempts, if experimental patterns with modern snails and their duraphagous predatory crabs (Vermeij, 1983) are extrapolated to these Cretaceous oysters. According to such an inverse relationship model, thinner valved pyncnodontids may have survived attacks less frequently, and therefore show fewer repairs.

Cementation may have evolved as an anti-predatory adaptation to shell crushers which must manipulate their prey in their claws (Harper, 1991). However, individuals of *P. mutabilis* occasionally remained cemented to a conspecific host throughout life and show extensive valve repair to the uppermost encrusting shell attached in presumed life position (Fig.1G). Because the pyncnodontids remained conjoined throughout life of the uppermost encruster, the predator, presumably a crab from the outline of the repaired fracture, manipulated a live, cemented specimen. Xenomorphic specimens which remained cemented to a substrate throughout much of their growth, usually develop a geniculate (upturned), free (idiomorphic), ventral valve margin that often has predatory scars (Fig. 1H). Cemented specimens were thus not necessarily less susceptible to predation by manipulative, clawed predators than free-lying individuals. Indeed, the exposed, thin geniculate margin of pyncnodontids may have invited more attacks relative to the less protruding ventral margin of free-lying non-geniculate exogyrid oysters.

Concerning the shell borers, telltale pinhole openings made by *C. cretacica* (Fig. 1B & F) are usually randomly distributed on the right (planar to concave) valves of both oyster species (Fig. 1J). However, left valves of *E. cancellata* show clionid boreholes preferentially concentrated in the dorsal area, particularly the beak (Fig. 2A). In contrast, left valve of *P. mutabilis* most frequently have a random distribution of clionid boreholes (Fig. 1D). The thickened beak of the left valve of exogyrids was exposed above the sediment surface while this oyster reclined in reconstructed life position. If settling clionid larvae behaved geotaxically and selectively metamorphosed on the elevated exposed areas, the left valve beak would be the most common site of initial infestation from which the clonal organism mined its way to other areas of the shell (Fig. 1F). That many exogyrid and pyncnodontid shells are not thoroughly riddled with boreholes over the entire surface, but show a concentration gradient of pinholes from the dorsal to ventral (Fig. 2A & B), or anterior to posterior margin (Fig. 1F), indicates that dorsal and anterior margins were commonly the initial cite of clionid infesation. Such gradients also indicate that a substantial percentage of the shells were buried before the clonal organism could spread to all parts of the shell. A veneer of permeable sediment will not deter a clionid from spreading to such thinly sand-covered areas, but more rapid, deeper burial in muddy sand could deny sufficient oxygenated water and food supply to these filter feeders.

Cretaceous oysters, like modern *Crassostrea virginica,* may have thickened their valves in response to infestations by clionids. One possible accretionary defense may have been the chambers most prominant in the beak area (Fig. 2D). Clionid borings commonly stop at shell laminae beneath which hollow chambers are situated (Fig. 2D). Larger (?*Polydora)* borings are often U-shaped and tangential to the chambered laminations (Fig. 2D), although it is not apparent how these borers would detect chambers beneath unbored laminae. The deterrance value of the valve internal structure may be overstated however, considering that clionids commonly saturated beaks with boreholes which penetrated to the shell interior. Nearly complete mechanical disintegration and/or chemical dissolution of the beak is common (Fig.1A).

Lithophagids are semi-endolithic suspension feeders, the posterior half of the valves often protruding above the shell hinge into which they bored (Fig. 2E). In the thinner center to ventral margin of the valves, lithophagids bored obliquely (Fig. 1A & 2F), whereas in the thicker dorsal region the bivalve bored nearly perpendicular to the valve surface (Fig. 2C & E). Lithophagids often clustered on the valve surface (Fig. 1A).

Only exposed portions of the valves, such as the beak of exogyrids (Fig. 1J) and pyncnodontids (Fig. 2C) would entice lithophagid larvae to settle or allow metamorphosed larvae to survive. A sediment veneer covering any portion of the shell would deter larval recruitment, which is why the most recessed portion of the concave right valve of pyncnodontids have a deficiency of lithophagids relative to the valve periphery (Fig.2F). Lithophagids may have survived to maturity on the thickest part of the valves near the hinge (Fig. 2C & E). The largest *Trypanites* boreholes are concentrated in the thick, dorsal anterior of the left valve of both species (Fig. 1J & 2C). Based on flume experiments with unidirectional currents across exogyrids in presumed life position, the dorsal anterior of the left valve where lithophagids are concentrated experienced sediment-scouring and turbulent flow in a unidirectional current. The eddies would have provided suspended food to the filter-feeding bivalve and kept the semi-endolthic borer free from accumulating sediment which lapped up against the ventral-posterior of the valve. *Trypanites* is uncommon to absent on the ventral portion of either valve (Fig. 1J). Thus lithophagid larvae may have displayed rheotaxic and geotaxic behavior, settling in the beak or dorsal-anterior area of the left valve. Mortality among metamorphosed larvae and juveniles may have been greatest where smothering sediment accumulated and the valves were thinnest (Fig. 2F). Given such disadvantages to settling larave, the ventral-posterior area of the shells should be deficient in lithophagid boreholes.

On overturned dead specimens, lithophagid larvae may have displayed geotaxic behavior, settling on the most elevated portion of the valve (Fig. 2B). Had the host been alive when the lithophagid bored into the left valve near the muscle scar area, the oyster may have secreted a callus-like deposit in the muscle scar area where the parasite was drilling toward the interior (Fig. 2G). Such deposits, combined with repair lamellae around *Trypanites* boreholes (Fig. 1D), can be used to differentiate lithophagid infestation of live hosts from boreholes drilled into overturned, dead hosts. However, not all callus deposits in the muscle scar area are associated with *Trypanites* on the valve exterior. Sediment irritation of the mantle, similar to that which stimulates for pearl formation in modern oysters, may have induced secretion of the callus deposits.

The size of the oyster valve and/or its thickness may have influenced infestation by lithophagids and clionids. Left valves of *E. cancellata* and *P. mutabilis* which lack borers have a mean dorsal-ventral length of 53 mm and 56 mm, respectively. They have an average valve thickness of 4.6 and 6.6 mm, respectively. Clionid and lithophagid-bored specimens of *E. cancellata* and *P. mutabilis* are, on average, significantly larger (91 mm and 74 mm, respectively), and thicker (9.5 mm and 11.8 mm), respectively. Two possible scenarios could account for the disparity in valve size between bored and unbored left valves of each species. With regard to thickness, the clionid and lithophagid larvae may have selectively settled on larger, and therefore probably thicker, valves to infest. Survival of the boring parasites would have been enhanced if the host valves were not so weakened that mechanical disintegration of the shell was inevitable. Alternatively, borers stimulated the host to ecophenotypically thicken its valves, as is the case with modern *Crassostrea virginica* . Similarly, the settling larvae may have preferentially metamorphosed on larger valve surfaces, or experienced lower mortality rate on larger valves of either species. Alternatively, all sizes of oysters may have been infested, but the smaller valves were substantially weakened and pulverized during transportation in the traction load, unrecognizably fragmented by predators, or disintegrated during post-mortem burial. Thus differences between size and thickness of bored versus unbored shells are statistically significant, but explanations for this disparity are debatable.

Even xenomorphic specimens show clionization in the broad flattened area where the valve was appressed against a firm substrate (Fig. 1H). Cementation to another shell was thus only a temporary deterrence to clionid infestation. The clionid was unlikely to bore through an encrusted shell to access an adjoining valve of another individual. However, once the epibiont shell became detached from its host, the xenomorphic area, which is often thinner than the geniculate, free, idiomorphic portion of the valve, is exposed to borers (Fig. 1H). Alternatively, clionid larvae initially colonized uncemented areas of valves and tunneled to the xenomorphic portion.

Multiple lithophagid boreholes are a better index of how long a valve remained exposed at the sediment surface than clionids which can tunnel and anastomose through the shell microstructure even if many areas of the valve are not exposed. As many as 35 lithophagid boreholes are found on a single exogyrid valve (Fig. 3C, whereas the maximum number of boreholes on a pyncnodontid is 18 (Fig 3D). For both species a single lithophagid borehole is most common, indicating that recruitment was restricted. Equal diameter, multiple *Trypanites* may represent a cohort, i.e, a single lithophagid spatfall that metamorphosed concurrently (Fig. 1J). However, specimens with multiple boreholes of drastically contrasting diameter (Fig. 2C) suggest that several generations of lithophagid larvae successfully colonized the host, although how many years the host shell resided at the sediment surface cannot be determined.

CONCLUSIONS

The convex left valves of *Exogyra cancellata* and *Pyncnodonte mutabilis* show multiple sublethal shell breakage, whereas the planar to concave right valves rarely show repairs. As many as seven repairs occur from the dorsal to the ventral margin of a large size valve, indicating that no size refuge from shell-crushing predators exited for these oysters species. Clionid borings are randomly distributed on the right valves of both oysters and the left valves of *P. mutabilis*. The sponge borings are concentrated on the dorsal beak area of left valves of *E. cancellata*, a valve region exposed above the sediment surface in life position. Lithophagid borings are concentrated in the dorsal-anterior region of the left valves of both oysters. These area regions of the shell which would experience turbulent flow and sediment-scouring. Settling larvae may have displayed rheotaxic (turbulence-seeking) and geotaxic(gravity-influenced) behavior in their site selectivity. Alternatively, mortality rates were differentiated across the valve surface, favoring survival of shell borers in the dorsal areas. Unbored right and left valves of either species are significantly thinner than their bivalve- and sponge-bored counterparts, a disparity which suggests valve size selectivity by the *Lithophaga* and *Cliona* settling larvae, or ecophenotypic thickening of the hosts shell in response to the infestation.

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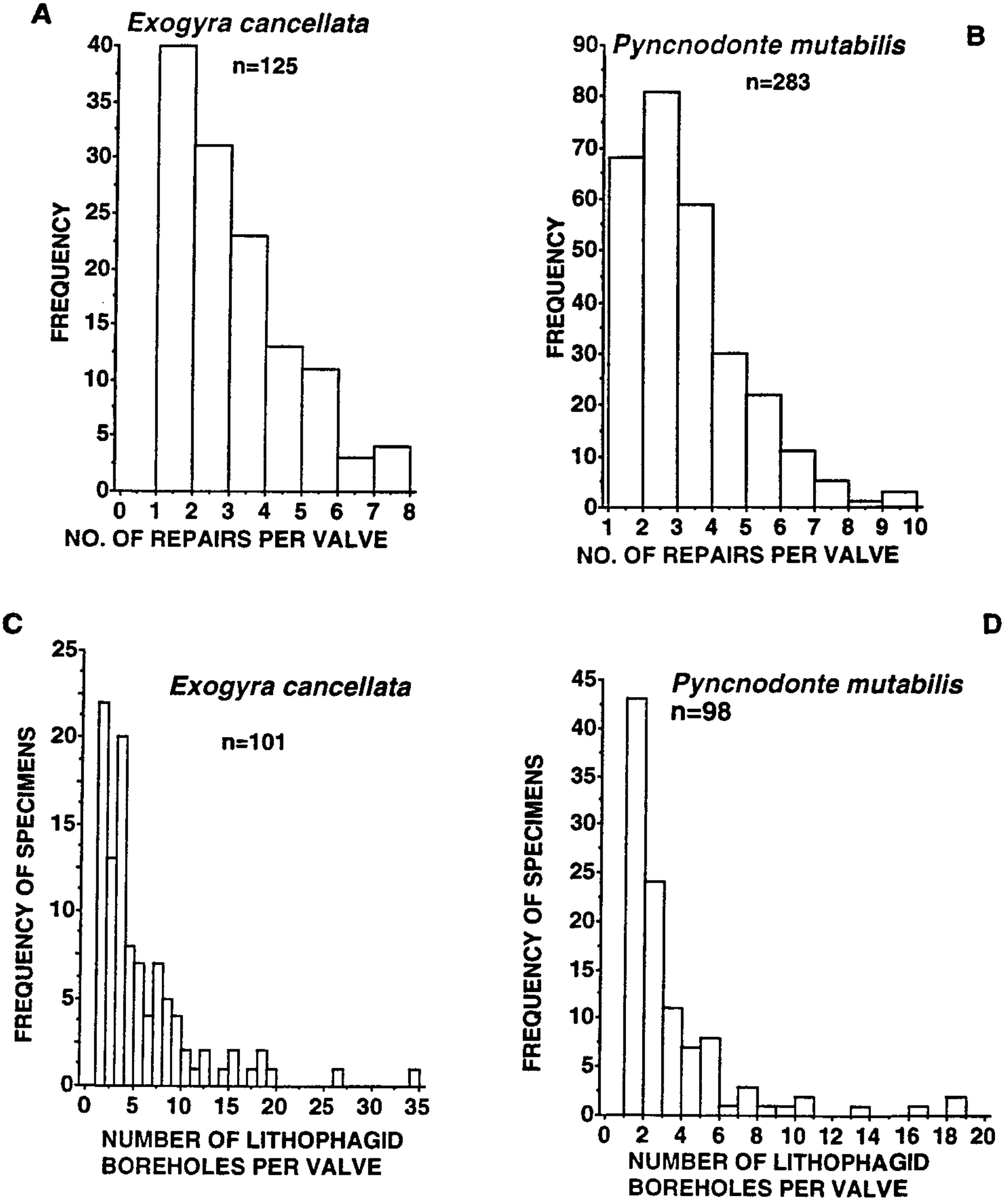
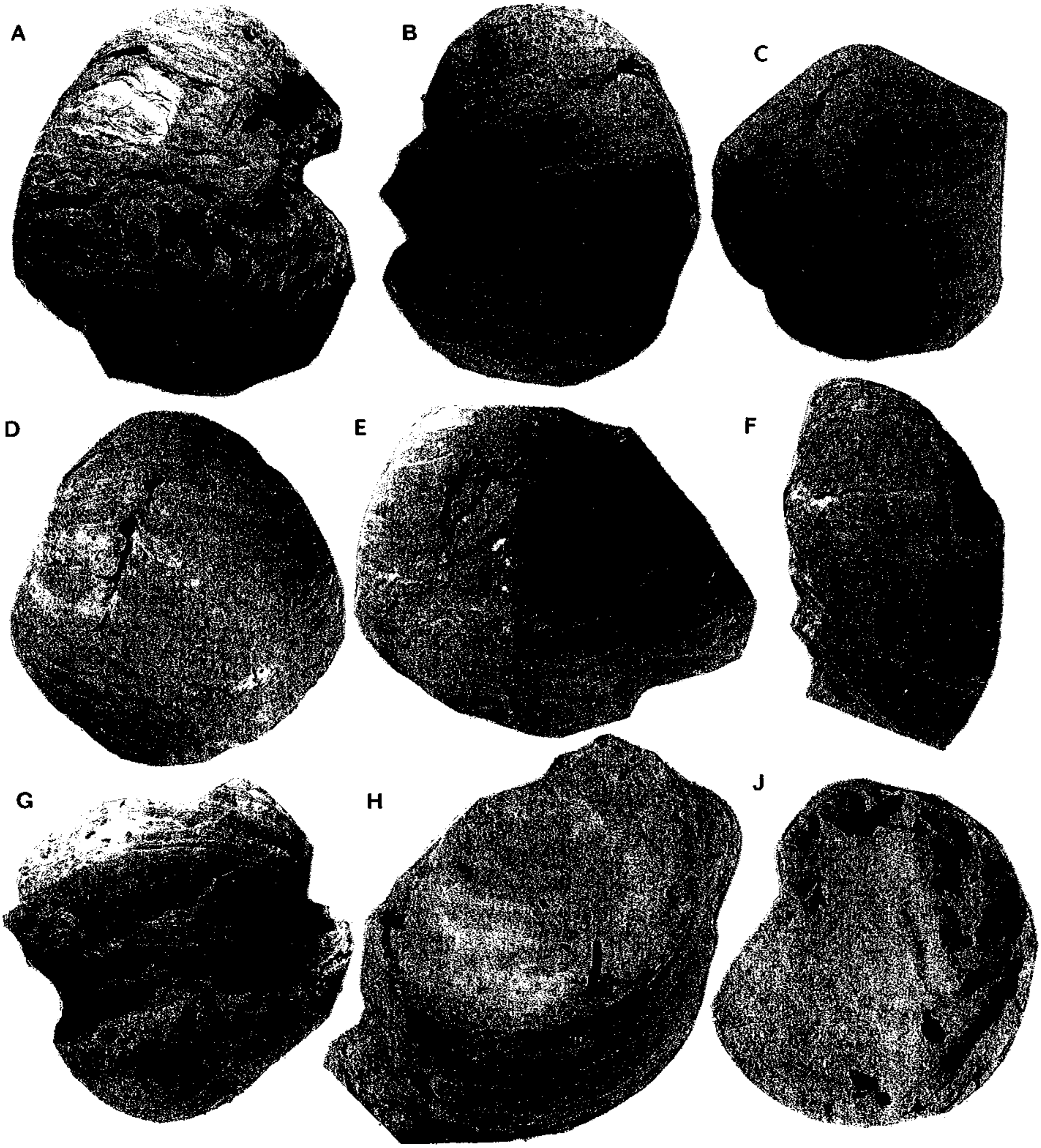


Figure 3. Frequencies of sublethal breakage repair in left valves (A, B) and lithophagid boreholes per valve (=*Trypanites* sp.) (C, D) in *E. cancellata* (A, C) and *P. mutabilis* (B, D).

Figure 1. Predation scars, clionid borings, and lithophagid borings in valves of *Exogyra cancellata* and *Pyncnodonte mutabilis*. A, F, and J are *E. cancellata.* All illustrations X 0.5 unless otherwise indicated. A.-Multiple, scalloped fracture pattern, thoroughly bioeroded beak, and cluster of three obliquely imbedded *Lithophaga ripleyana* near center-ventral portion of left valve. B-Multiple scalloped fracture patterns and dorsal-posterior to ventral-posterior concentration of clionid borings in left valve. C-Meandering cleft projecting from ventral marginto beak area of left valve. Note growth lines "V" dorsally across recessed area of left valve. X 0.7. D-Cleft terminating dorsally in lithophagid borehole (=*Trypanites* sp.) Note random distribution of clionid boreholes over entire valve surface. E-Embayed fracture pattern in central portion of clionid borehole-free left valve. X 0.6. F-Multiple scalloped fractures from dorsal to ventral margin and anteriorly concentrated clionid borings in left valve. G-Left valve concave-up and cemented at its dorsal hinge to concave-up, conspecific left valve. Note repaired embayment in uppermost left valve. H-Xenomorphic, flattened, dorsal half of left valve with geniculate, ventral, idiomorphic portion. Note clionid boreholes in dorsal margin of once cemented, xenomorphic area. Also note repaired divot in geniculate ventral margin to lower left. X 1.0 J-Random clionid borehole distributions and anteriorly concentrated, similar diameter *Trypanites* sp. borings in planar right valve.

Figure 2- Predation scars, "callus" deposits in muscle scars, clionid borings, and lithophagid borings in valves of *Exogyra cancellata* and *Pyncnodonte mutabilis*. A, D, and G are *E. cancellata.* All illustrations times 0.5 unless otherwise indicated. A-Multiple scalloped fracture pattern and dorsally concentrated clionid borings in left valve. B-Dorsally concentrated clionid borings and a single *Trypanites* sp. in center of left valve. C-Beak and anteriorly concentrated, variable diameter *Trypanites* sp. in left valve. D-Chambers among lamina nearer interior of dorsal margin of left valve. Dark lithified infillings of clionid borings and U-shaped *?Polydora* adjacent to, but not penetrating, zone of chambered laminae. X 2.5. E-Posterior half of shell of *Lithophaga ripleyana* protruding from hinge area where bivalve bored perpendicularly into beak area of left valve. X 2.0. F-Obliquley oriented *Trypanites* sp. around margin of concave right valve exterior. Note absence of borings in most recessed, central portion of valve. G-"Callus-like" deposits in adductor muscle scar area of right valve. X 1.0.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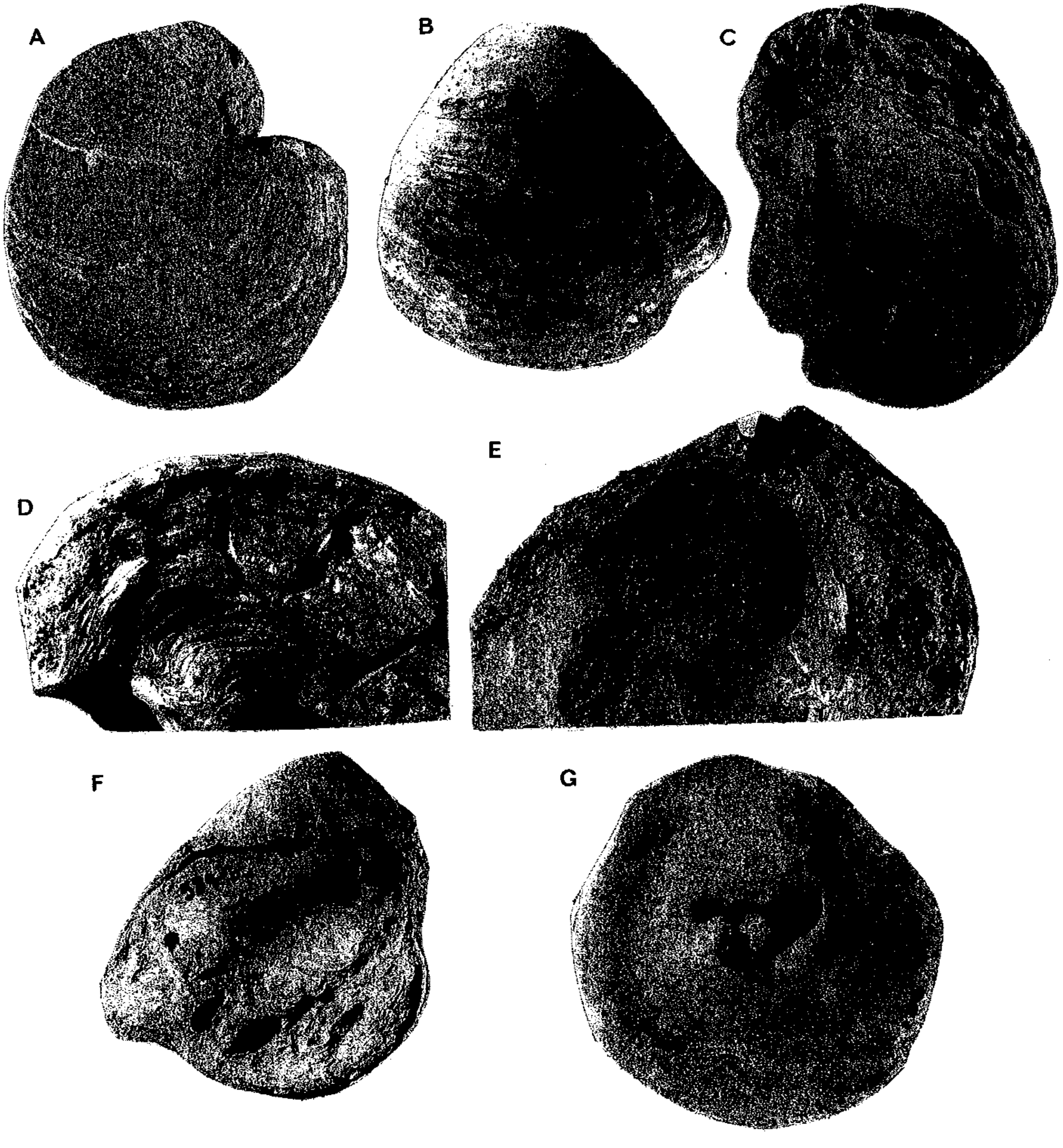
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FOSSIL SHARK REMAINS FROM THE EARLY AND MIDDLE MAASTRICHTIAN OF THE UPPER CRETACEOUS OF MONMOUTH COUNTY, NEW JERSEY

By GERARD RAMON CASE

INTRODUCTION

In the year 1975, this author co-authored a large paper on the study of the selachians (sharks, skates, rays and sawfishes) of the Mt. Laurel and Navesink Formations of New Jersey.

Cappetta and Case (1975) were under the impression at that time, that the Mt. Laurel Formation was Late Campanian in age, and that the Navesink Formation was from the Early Maastrichtian stage. The geology has been corrected since then. Dr. Sunday W. Petters, a geologist from Lagos, Nigeria in Africa, was studying here in the United States in the Early 1970's, and one of his projects was Atlantic Coastal Plain geology. After the Cappetta and Case report was published, Petters came out with his paper entitled: "Upper Cretaceous subsurface stratigraphy of the Coastal Plain of New Jersey". In this work, Petters (1976) states that the Mt. Laurel is in actuality, Early Maastrichtian, and that the Navesink was from the Middle Maastrichtian stage.

One more up-dating (correction) to the Cappetta and Case report of 1975 is significant, and should be addressed here. That is, that of all the twenty eight species described by Cappetta and Case (ten of which were new to the science of Paleontology), only twenty six were in fact from the Early and Middle stages of the Maastrichtian, while one of the described taxa was in actuality from the Navarro Group, Late Maastrichtian stage. This specimen was <u>Serratolamna</u> <u>serrata</u> (Agassiz), while <u>Cretoxyrhina</u> <u>mantelli</u> (Agassiz) <u>was from the</u> <u>Santonian</u> srage of the <u>Cretaceous</u> (<u>Case and</u> Schwimmer, 1988 and Case and Cappetta, 1995).

GEOLOGY

Petters (1976:91) places the entire Maastrichtian stage in the Monmouth Group. That is, the Early, Middle as well as the Late Maastrichtian. This present author does not entirely agree with Petters on this. In most states in North America (such as Texas (Case and Cappetta, 1995), and Maryland, in particular, the Late Maastrichtian is considered to be in the Navarro Group.

So, I grant that Petters was right in assigning the Mount Laurel to the Early Maastrichtian stage and the Navesink to the Middle Maastrichtian stage. The fauna of the Late Maastrichtian stage is quite different from the faunas of the Early and Middle stages of the Maastrichtian. Case and Cappetta (1995) have just prooved this in their latest report entitled: "A new selachian fauna from the Late Maastrichtian of Texas (Upper Cretaceous/Navarroan; Kemp Formation)". Case and Cappetta introduce a fauna that is more than 50% different from their earlier monograph of the Early and Middle Maastrichtian of New Jersey.

Case and Cappetta (1995) introduced in the North American paleontological record the following new genera and new species which are recorded for the first time in North American paleontology: *Heterodontus granti*; *Squalus huntensis*; *Cantioscyllium meyeri*; *Plicatoscyllium antiquum*; *Plicatoscyllium derameei*; *Carcharias heathi*; *Anomotodon toddi*; *Scyliorhinus ivagrantae*; *Squatigaleus sulphurensis*; *Palaeogaleus navarroenis*; *Rhinobatos uvulatus*; *Rhinobatos craddocki*; *Raja farishi*; *Ischyrhiza monasterica*; *Sclerorhynchus pettersi*; *Ptychotrygon winni*; *Dasyatis commercensis*; *Coupatezia turneri*; *Hamrabatis weltoni*; *Texabatis corrugata*; and *Ewingia problematica*.

Although all of the above twenty one species (three of which, are new genera: *Plicatoscyllium*, *Texabatis* and *Ewingia*) are new to science, there appears in the Late Maastrichtian of Texas, only these few taxa found in the Early Maastrichtian Mt. Laurel Formation, and the Middle Maastrichtian Navesink Formation of New Jersey: *Lissodus babulskii* (Cappetta and Case), *Squalicorax kaupi* (Agassiz): *Squalicorax pristodontus* (Agassiz); *Carcharias holmdelensis* (Cappetta and Case); *Carcharias samhammeri* (Cappetta and Case); *Odontaspis aculeatus* (Cappetta and Case); *Ischyrhiza mira* Leidy; and *Ptychotrygon vermiculata* Cappetta.

The total fauna (updated March 1995) of selachians described by Cappetta and Case from the Early and Middle Maastrichtian of New Jersey is as follows:

Hybodus sp. 1
Hybodus sp. 2
Lissodus babulskii (Cappetta and Case)
Heterodontus sp. (as yet, undescribed)
Squalicorax kaupi (Agassiz)
Squalicorax pristodontus (Agassiz)
Pseudocorax aff. *affinis* (Münster)(as yet, undescribed)
Squatina hassei Leriche
Cretolamna appendiculata lata (Agassiz)
Serratolamna serrata (Agassiz)(Late Maastrichtian)
Cretoxyrhina mantelli (Agassiz)(Late Santonian)
Cretodus borodini (Cappetta and Case)
Archaeolamna kópingensis kopingensis (Davis)
Paranomotodon cfr. *angustidens* (Reuss)
Scapanorhynchus texanus (Roemer)
Odontaspis aculeatus (Cappetta and Case)
Carcharias holmdelensis (Cappetta and Case)
Carcharias hardingi (Cappetta and Case)
Carcharias samhammeri (Cappetta and Case)
Chiloscyllium sp.
Hemiscyllium sp.
Ginglymostoma globidens Cappetta and Case
Rhinobatos casieri Herman
Ischyrhiza avonicola Estes
Ischyrhiza mira Leidy
Ankistrorhynchus major Cappetta and Case
Ptychotrygon cuspidata Cappetta and Case
Ptychotrygon vermiculata Cappetta
Brachyrhizodus wichitaensis Romer
Rhombodus levis Cappetta and Case

Two of the above selachians have not been described as yet from the Maastrichtian of New Jersey: *Heterodontus* sp. from the Mt. Laurel Formation (Early Maastrichtian), and *Pseudocorax* aff. *affinis* (Münster) from the Middle Maastrichtian Navesink Formation.

Case (1978 and 1987) described the following species from the Campanian and Late Campanian of Montana (Judith River Formation) and Wyoming (:Mesaverde" Formation)--Montana: *Hybodus montanensis*; *Hybodus storeri*; *Paraorthacodus andersoni*; *Paraorthacodus striatus*; *Squalicorax kaupi*; *Archaeolamna kopingensis kopingensis*; *Odontaspis grandis*; *Eucrossorhinus microcuspidatus*; *Cretorectolobus olsoni*; *Carcharias sanguinei*; *Archaeotriakis rochellae*; *Protoplatyrhina renae*; *Ischyrhiza avonicola*; *Ischyrhiza* sp.; *Ptychotrygon blainensis*; and *Myledaphus bipartitus*. All of the above are from the Judith River Formation. From the :Mesaverde" Formation of Wyoming, we now have: *Hybodus montanensis*; *Hybodus wyomingensis*; *Lissodus griffisi*; *Synechodus turneri*; *Scapanorhynchus texanus*; *Archaeolamna kopingensis kopingensis*; *Squalicorax kaupi*; *Squalicorax pristodontus*; *Squalus worlandensis*; *Scyliorhinus tensleepensis*; *Odontaspis grandis*; *Carcharias cheathami*; *Carcharias steineri*; *Pseudodontaspis herbsti*; *Ginglymostoma globidens*; *Eucrossorhinus microcuspidatus*; *Cretorectolobus olsoni*; *Chiloscyllium missouriensis*; *Brachaelurus bighornensis* *Ischyrhiza roessingi*; *Archaeotriakis rochelleae*; *Archaeotriakis ornatus*; *Rhinobatos casieri*; *Protoplatyrhina renae*; *Ischyrhiza avonicola*; *Ischyrhiza basinensis*; *Ischyrhiza mira*; *Ankistrorhynchus washikiensis*; *Ptychotrygon boothi*; *Ptychotrygon ellae*; *Ptychotrygon greybullensis*; and *Myledaphus bipartitus*.

In 1987, Case also described a sclerorhynchid sawfish rostral spine from the Upper Blufftown Formation (Campanian) of Georgia. Its name is: *Borodinopristis schwimmeri* (Case, 1987b.).

Other Cretaceous selachian specimens were described by Case (1979), Case, Tokaryk and Baird (1990), Case and Schwimmer (1988), and Case (1991). Case also described an Upper Cretaceous chimaeroid fish jaw from the Navesink Formation of New Jersey: *Ischyodus bifurcatus* (Case, 1978).

One final note here regarding Cretaceous shark's teeth - In 1992, Manning and Dockery put out a publication (for amateur collectors) on the shark's teeth and other fossil remains (turtles, dinosaurs, etc.) of the Demopolis Chalk (Campanian) of northern Mississippi. In this report, there are many errors, particularly in nomenclature. I wish to point out one gross error and another which is not as critical, but is nevertheless bad for scientific knowledge.

The first error is Manning and Dockery's calling Cappetta and Case's *Ginglymostoma globidens*: *Cantioscyllium descipiens globidens*, and the other nomenclatural fauxpas is: calling *Scapanorhynchus texanus* (Roemer) *Scapanorhynchus raphiodon texanus* - thus giving the genus of goblin shark two species names, when in all likelihood the authors meant to give the genus a subspecies name (a practice which is frowned upon nowadays by the scientific community). Manning and Dockery should have given Scapanorhynchus either the species name of *raphiodon* or *texanus*.

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ACKNOWLEDGEMENTS

Special thanks to my colleague, Dr. Henri Cappetta, Montpellier, France. Photographs of teeth by Mr. Richard E. Grant, Farmers Branch, Texas. Pen and ink drawings by the author.

This work is dedicated to the memory of a fine lady, Miss Laura Harding of Holmdel, New Jersey, who passed away on August 8, 1994 at the age of 92 years, and also to her long-time friend, Miss Katherine Hepburn, a superb actress, we are proud to have her among us still.

Plate 1

1. *Hemiscyllium* sp. (Labial aspect).
2. *Chiloscyllium* sp. (Labial aspect).
3. *Ptychotrygon cuspidata* Cappetta & Case (Occlusal view).
4. *Ptychotrygon vermiculata* Cappetta (Occlusal view).
5. *Hybodus* sp. 1. (Labial view).
6. *Hybodus* sp. 2. (Occlusal view).
7. *Rhinobatos casieri* Herman(Occlusal view).
8. *Ankistrorhynchus major* Cappetta & Case (Rostral spine-posterior face).
9. *Ischyrhiza mira* Leidy (Rostral spine-superior face).
10. *Odontaspis aculeatus* (Cappetta & Case)(Labial aspect).
11. *Brachyrhizodus wichitaensis* Tomer (Basal aspect).
12. *Ischyrhiza avonicola* Estes (Rostral spine-anterior face).
13. *Ischyrhiza avonicola* Estes (Oral tooth).
14. *Ginglymostoma globidens* Cappetta & Case (Labial aspect).
15. *Rhombodus levis* Cappetta & Case (Lingual aspect).
16. *Lissodus babulskii* (Cappetta & Case)(Occlusal aspect).

Plate 2

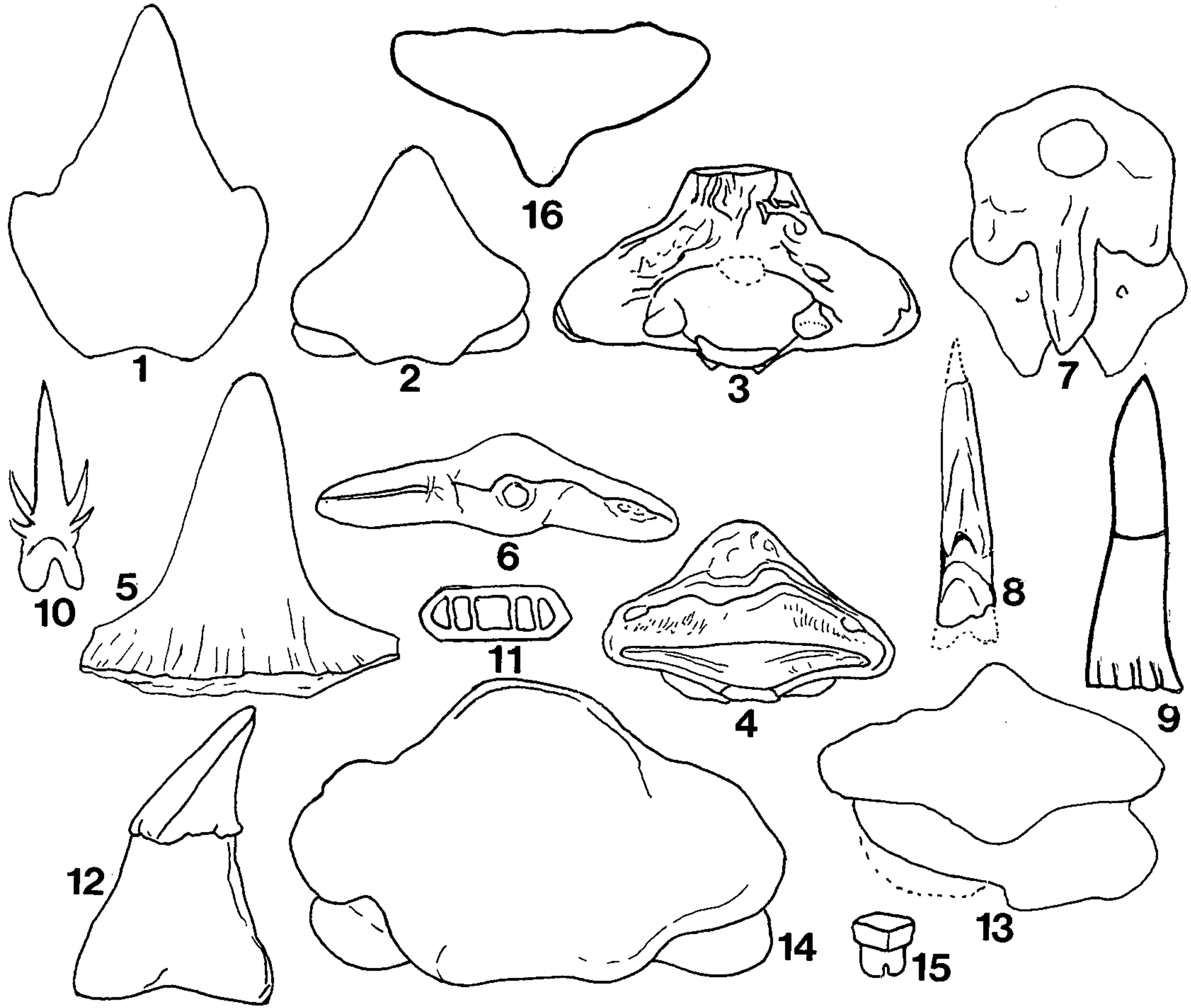
1. *Squalicorax kaupi* (Agassiz)(Anterior tooth-lingual aspect).
2. *Squalicorax kaupi* (Agassiz)(Anterior tooth-labial aspect).
3. *Squalicorax kaupi* (Agassiz)(Latero-posterior tooth-lingual aspect).
4. *Squalicorax kaupi* (Agassiz)(Latero-posterior tooth-labial aspect).
5. *Squalicorax pristodontus* (Agassiz)(Anterior tooth-lingual aspect).
6. *Squalicorax pristodontus* (Agassiz)(Anterior tooth-labial aspect).
7. *Squalicorax pristodontus* (Agassiz)(Antero-lateral tooth-Labial view).
8. *Squalicorax pristodontus* (Agassiz)(Antero-lateral tooth-lingual view).
9. *Cretodus borodini* (Cappetta & Case)(Anterior tooth-lingual aspect).
10. *Cretodus borodini* (Cappetta & Case)(Anterior tooth-labial aspect).
11. *Cretodus borodini* (Cappetta & Case)(Anterior tooth-lingual aspect).
12. *Cretodus borodini* (Cappetta & Case)(Anterior tooth-labial aspect).
13. *Archaeolamna kopingensis kopingensis* (Davis)(Anterior tooth-profile).

Plate 3

1. *Archaeolamna kopingensis kopingensis* (Davis)(Antero-lat.tooth, lingual).
2. *Archaeolamna kopingensis kopingensis* (Davis)(Antero-lat. tooth, labial).
3. *Archaeolamna kopingensis kopingensis* (Davis)(Anterior tooth-lingual).
4. *Archaeolamna kopingensis kopingensis* (Davis)(Anterior tooth-labial view).
5. *Paranomotodon* cf. *angustidens* (Reuss)(Lateral tooth-lingual view).
6. *Paranomotodon* cf. *angustidens* (Reuss)(Lateral tooth-labial view).
7. *Squatina hassei* Leriche (Lateral tooth-basal view).
8. *Squatina hassei* Leriche (Lateral tooth-profile view).
9. *Squatina hassei* Leriche (Lateral tooth-labial view).
10. *Squatina hassei* Leriche (Lateral tooth-Occlusal view).
11. *Squatina hassei* Leriche (Lateral tooth-lingual view).

Plate 4

1. *Scapanorhynchus texanus* (Roemer)(Anterior tooth-lingual view).
2. *Scapanorhynchus texanus* (Roemer)(Anterior tooth-labial view).
3. *Scapanorhynchus texanus* (Roemer)(Antero-lateral tooth-lingual view).
4. *Scapanorhynchus texanus* (Roemer)(Antero-lateral tooth-labial view).
5. *Scapanorhynchus texanus* (Roemer)(Lateral tooth-lingual aspect).
6. *Scapanorhynchus texanus* (Roemer)(Lateral tooth-labial aspect).
7. *Cretolamna appendiculata* (Agassiz)(Lateral tooth-lingual view).
8. *Cretolamna appendiculata* (Agassiz)(Lateral tooth-labial view).
9. *Rhinobatos casieri* Herman (Occlusal view-Antero-lateral tooth).
10. *Rhinobatos casieri* Herman (Basal view-Antero-lateral tooth).
11. *Carcharias holmdelensis* (Cappetta & Case)(Ling. view-Antero-lat. tooth).
12. *Carcharias holmdelensis* (Cappetta & Case)(Lab. view-Antero-lateral tooth)
13. *Carcharias samhammeri* (Cappetta & Case)(Lingual view-Anterior tooth).
14. *Carcharias samhammeri* (Cappetta & Case)(Lingual view-Lateral tooth).
15. *Carcharias samhammeri* (Cappetta & Case)(Labial view-Lateral tooth).
16. *Carcharias hardingi* (Cappetta & Case)(Lingual view-Anterior tooth).
17. *Carcharias hardingi* (Cappetta & Case)(Labial view-Anterior tooth).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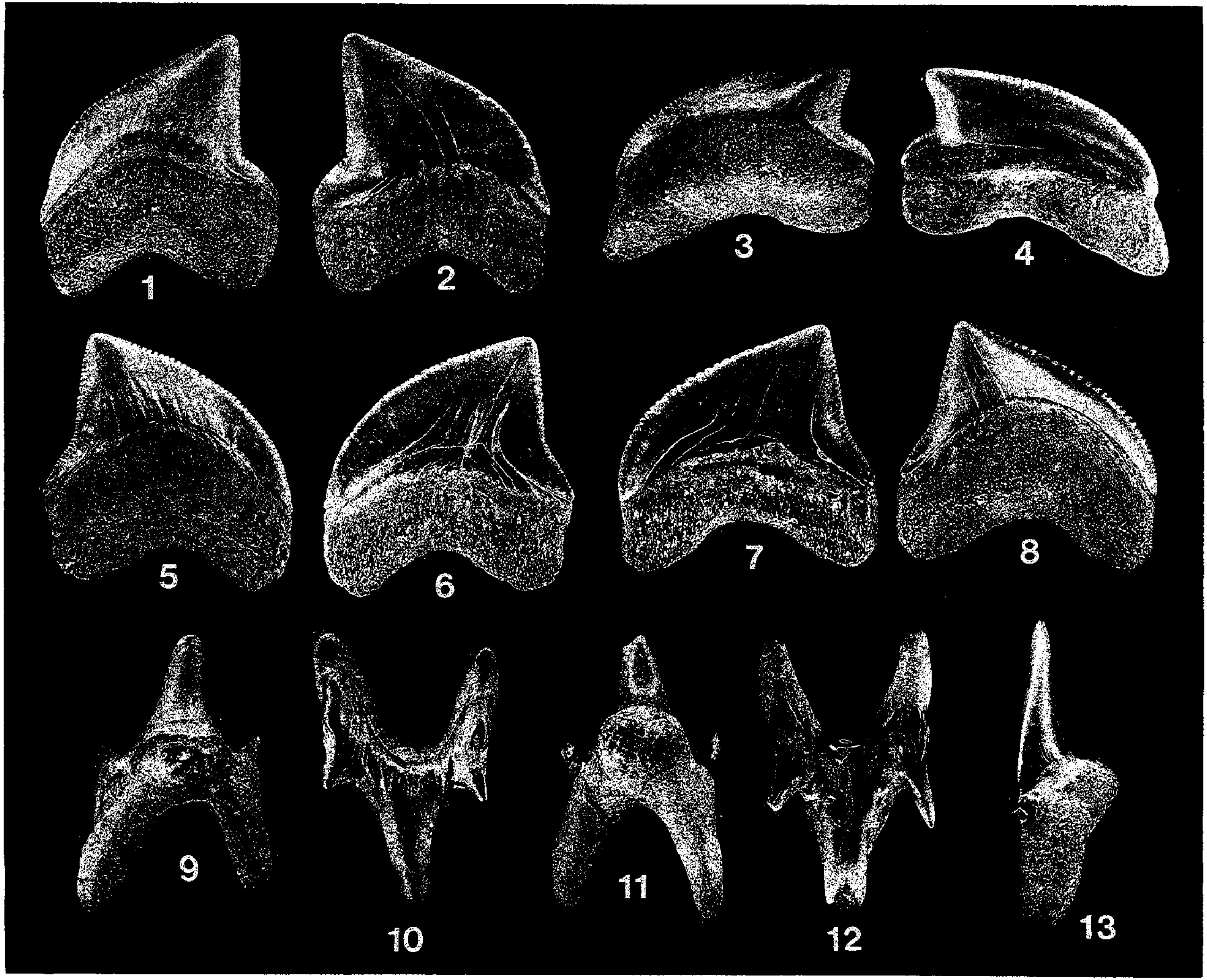
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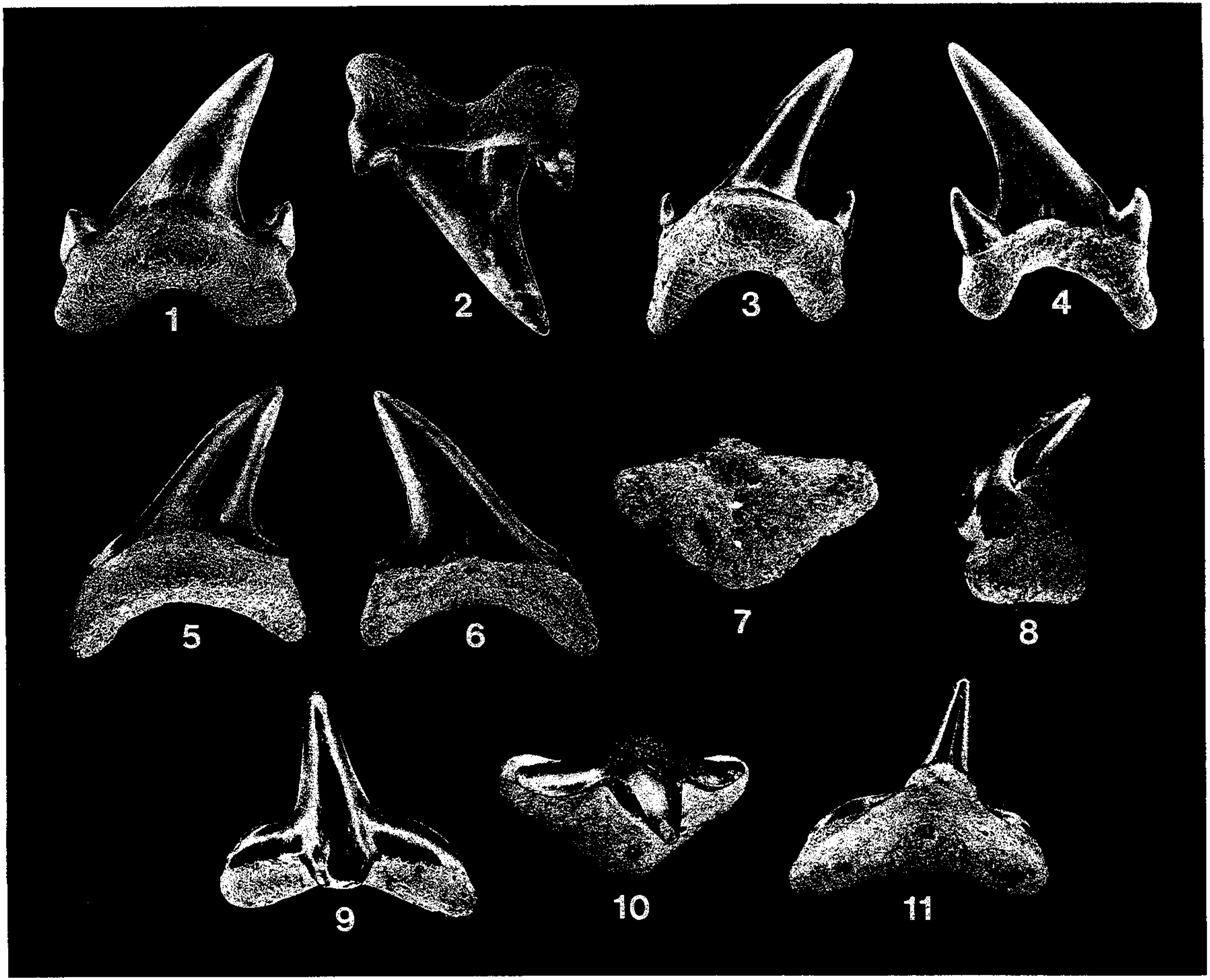
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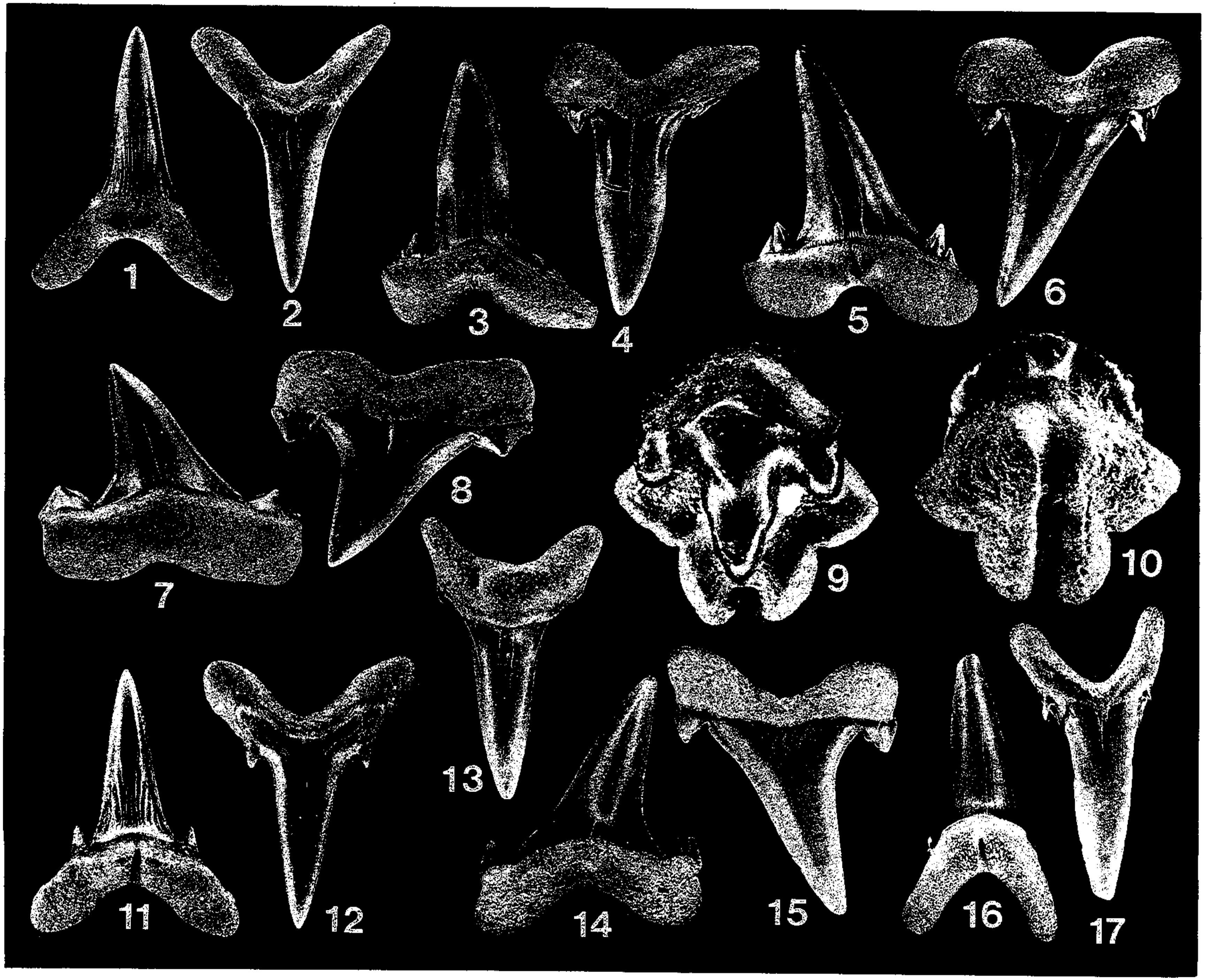
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Macroinvertebrate Faunas of the Englishtown Formation (Campanian)

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Abstract - A paleontological examination was conducted on the Englishtown formation. This unit was found to be fossiliferous at two localities in southwestern New Jersey: Auburn and Cherry Hill. At both localities, bivalves dominate numerically and taxonomically.

Introduction

The Englishtown formation has long been considered to be poorly fossiliferous in New Jersey (see Weller, 1907; Kummel, 1940; Richards et al, 1958; Owens and Sohl, 1969; Sohl, 1977a). In fact, no identifiable macrofossils (besides the ubiquitous trace-fossil *Ophiomorpha*) were known from this unit until Richards et al, (1958) reported the bivalve *Granocardium tenuistriatum* and the gastropods *Euspira halli* and *Turritella* in a well core taken at Lavalette (Ocean County, NJ). Soon thereafter, Owens and Minard (1966) noted the bivalve *Cymella bella* in Englishtown outcrops near Allentown (Monmouth County, NJ).

Recent reports of a diverse fauna (57 species representing 51 genera) contained within the basal portion of the Englishtown in Mount Laurel township (see Bonfiglio et al, 1987; Kuehne, 1993) necessitated a paleontological reexamination of the unit. Surprisingly, the present field work confirms not only that the Englishtown is indeed abundantly fossiliferous at several other widespread locations, but also that it locally contains one of the most diverse Upper Cretaceous macroinvertebrate faunal assemblages found within the confines of New Jersey.

The localities described below expose the dark-gray silty sand facies of the Englishtown formation discussed by Owens and Sohl (1969, p. 244, 245). This facies predominates in the southwestern part of the state and contains, in addition to quartz sand, an abundance of mica (especially muscovite) and varying amounts of clay (Minard, 1965). One site (Auburn) lies within Salem County (see Fig. 1) and the other (Cherry Hill) lies within Camden County (see Fig. 2).

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Auburn Locality

The Auburn site consists of low streambank outcroppings along a small, secondary tributary of Oldmans Creek. Here, a diverse macroinvertebrate fauna (245 specimens belonging to 49 species and 37 genera: see Table 1) was collected from a dark-gray, micaceous, clayey silt bed measuring 0.6m in thickness. This interval grades downward into an unfossiliferous plastic clay and is unconformably overlain by the quartz-glauconite sands of the Marshalltown formation.

Both calcitic and aragonitic taxa are preserved as original shell material (a relatively rare occurrence in the New Jersey Upper Cretaceous). The scaphopod *Dentalium inornatum* and the small bivalves *Lucina parva, Striarca umbonata*, and *Caestocorbula foulkei*, numerically dominate the assemblage. Dominant among the larger taxa are the gastropod *Haustator quadrilira*, the inarticulate brachiopod *Lingula subspatulata*, and the bivalves *Cyprimeria depressa*, *Tellina georgiana*, and *Veniella conradi*. The abundance of *L. subspatulata* is certainly one of the most unique aspects of the Auburn fauna.

Cherry Hill Locality

At Cherry Hill (Camden County, NJ), streambank exposures along Tindale Run (a tributary of the Cooper River) expose the Marshalltown and upper Englishtown formations downstream from Route 561. At this locality, the upper Englishtown consists of fossiliferous, dark-gray, micaceous, sandy, clayey silt, with small pockets of nearly pure quartz sand. A diverse fauna (130 specimens representing 26 species and 23 genera: see Table 1) was recovered. Preservation consists of clay casts and molds. With the exception of the bivalve *Cymella bella*, the fauna has few clear dominants.

Infaunal/Epifaunal Ratio

The ratio of infaunal to epifaunal macroinvertebrate taxa is an important paleoecological tool (Boucot, 1981). In general, this ratio is higher in fine-grained sediments and lower in coarse matrices.

Kuehne (in preparation) has calculated the infaunal/epifaunal ratio for the bivalve faunas contained in each New Jersey Late Cretaceous formation. This evidence indicates that coarse-grained units (e.g. the Mount Laurel and Tinton formations) have an infaunal/epifaunal ratio below 1.0 and fine-grained units (e.g. the Magothy and Wenonah formations) have a ratio above 1.0. The Englishtown bivalve fauna has an infaunal/epifaunal ratio of 1.86, indicative of the fine-grained nature of that unit in the southwestern portion of New Jersey.

Acknowledgments

I take this opportunity to thank Mr. Tighe (owner of the Auburn locality) for his generous permission to collect specimens from his property. I am also grateful to William Kuehne who generously provided field assistance at the Cherry Hill site. This article was kindly reviewed by William Gallagher of the New Jersey State Museum.

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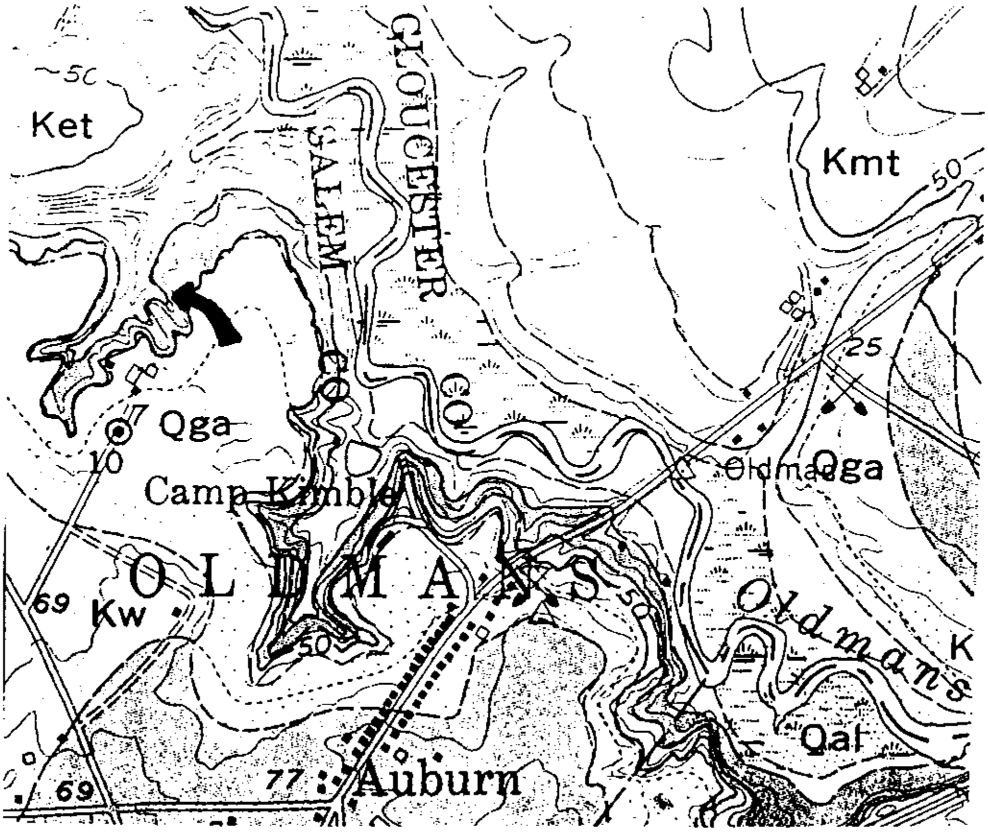
Table 1

Macroinvertebrate faunal list for the Auburn and Cherry Hill localities.

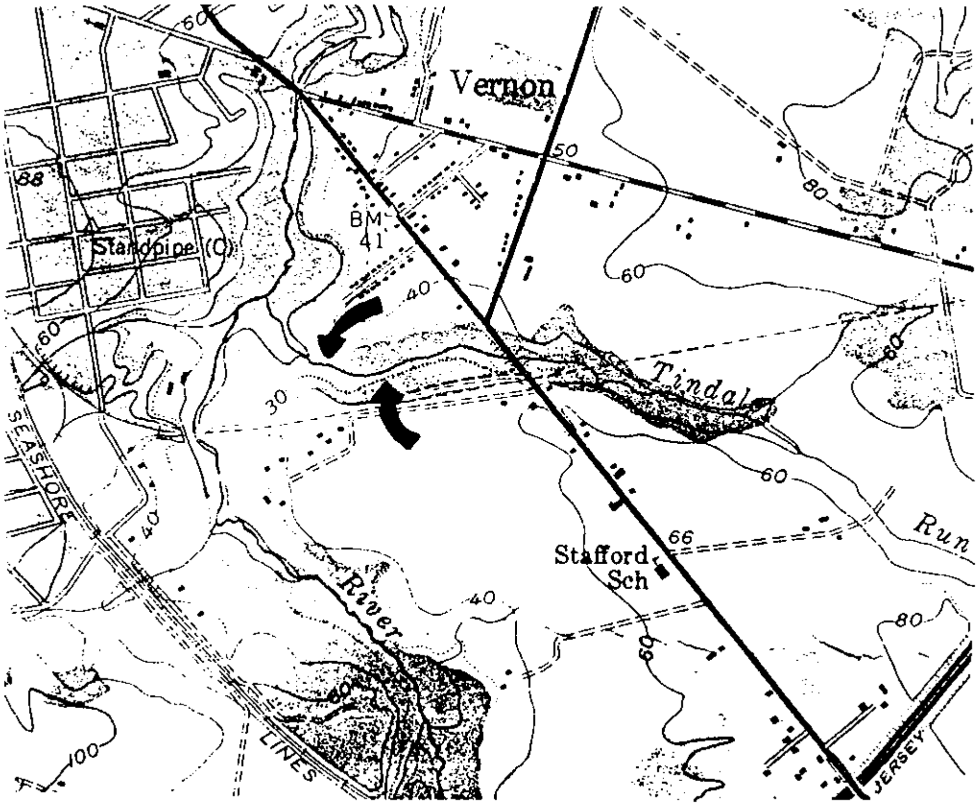
	Auburn	**Cherry Hill**
Annelida		
Hamulus falcata (Conrad)	X	
Brachiopoda		
Lingula subspatulata Hall & Meek	X	
Pelecypoda		
Nucula percrasssa Conrad		X
Nucula slackiana (Gabb)	X	
Nuculana littlii (Gardner)		X
N. longifrons (Conrad)	X	X
N. stephensoni Richards	X	
N. aff. *N. rostratruncata* (Gardner)	X	
N. cf. *N. whitfieldi* (Gardner)		X
Barbatia spp.	X	
Nemodon cf. *N. angulatum* (Gabb)	X	
N. brevifrons Conrad	X	
N. eufaulensis (Gabb)	X	
Striarca haddonfieldensis (Stephenson)	X	X
S. umbonata (Conrad)	X	X
Glycymeris sp.	X	
Lycettia cf. *L. tippana* (Conrad)		X
Pteria petrosa (Conrad)	X	
Gervillia ensiformis (Conrad)	X	
Syncyclonema simplicium (Conrad)	X	X
Camptonectes bellisculptus (Conrad)	X	
Anomia argentaria Morton	X	X
Lima pelagica (Morton)	X	
L. reticulata Lyell & Forbes		X
Ostrea sp.	X	
Pterotrigonia eufaulensis (Gabb)	X	X

Lucina parva Stephenson	X	X
Crassatella sp.	X	X
C. hodgei (Stephenson)	X	
Granocardium sp.	X	
Granocardium dumosum (Conrad)		X
Pleuriocardia eufaulensis (Conrad)	X	
Cymbophora cf. *C. lintea* (Conrad)	X	X
Leptosolen biplicata Conrad		X
Aenona eufaulensis (Conrad)	X	
Linearia metastriata Conrad		X
Tellina sp.		X
T. gabbi Gardner	X	
T. cf. *T. georgiana* Gabb	X	
Etea carolinensis Conrad	X	
Tenea parilis (Conrad)	X	
Veniella conradi Morton	X	X
Aphrodina tippana jerseyensis Richards	X	X
Cyprimeria depressa (Conrad)	X	X
Caestocorbula foulkei (Lea)	X	X
Caestocorbula crassiplica (Gabb)	X	
Pholas sp.		X
Xylophagella irregularis? (Gabb)	X	
Anatimya? sp.	X	
Cymella bella texana Stephenson	X	X
Gastropoda		
Haustator quadrilira (Johnson)	X	X
Pyropsis sp.	X	
Cancellaria smocki Weller	X	
Scaphopoda		
Dentalium inornatum Wade	X	
D. subarcuatum Conrad	X	
Cephalopoda		
Baculites ovatus Say	X	
Placenticeras placenta (DeKay)	X	
Crustacea		
Protocallianassa mortoni (Pilsbry)	X	X



Woodstown 7.5' Quadrangle

Fig. 1 AUBURN LOCALITY



Camden 7.5' Quadrangle

Fig. 2 CHERRY HILL LOCALITY

Ostracode Biostratigraphy of the Upper Cretaceous Marine Sediments in the New Jersey Coastal Plain

By **Gregory S. Gohn** (U.S. Geological Survey, Reston, VA 22092)

ABSTRACT

Six informal ostracode biozones are proposed for the Upper Cretaceous marine sections of New Jersey. These zones are documented in drill-hole sections correlated to the Cretaceous outcrop section. The zones, their subzones and ages, and their generally correlative outcrop units are 1) Cenomanian taxon range zone Ce/t1 (Bass River Formation, subsurface only), 2) lower Campanian assemblage zone Ca/a1 (four subzones; Merchantville Formation and Woodbury Clay), 3) middle Campanian assemblage zone Ca/a2 (three subzones; Woodbury Clay and marine sections of the Englishtown Formation), 4) upper Campanian assemblage zone Ca/a3 (Marshalltown and Wenonah Formations, lower part of the Mount Laurel Sand), 5) upper Campanian partial range zone Ca/p4 (upper part of Mount Laurel Sand), and 6) Maastrichtian assemblage zone Ma/a1 (two subzones; Navesink Formation and Sandy Hook Member of the Red Bank Formation). Thirty-four ostracode species are illustrated.

INTRODUCTION

Calcareous marine sediments are present in two stratigraphic intervals within the Upper Cretaceous Series of the New Jersey Coastal Plain, the Cenomanian to Turonian section and the Campanian to Maastrichtian section. Included in the locally abundant microfauna in these sediments are the Ostracoda, a group of dominantly benthic, small, bivalved crustaceans that have hinged external carapaces of calcified chitin. Ostracode assemblages have been reported from the New Jersey Cretaceous sections by Jennings (1936), Nine (1954), Adams (1960), Brouwers and Hazel (1978, text-fig. 3), and Gohn (1992a, b).

In addition, the regional ostracode zonations of Brown and others (1972) and Hazel and Brouwers (1982; also see Pitakpaivan and Hazel, 1994) have been applied to the New Jersey sections. The Late Cretaceous concurrent-range zones and assemblage zones of Brown and others (1972, table 2, p. 41-45) use relatively few ostracode species and have long durations; each zone is approximately equivalent to a provincial Cretaceous stage. Further, some of the characteristic species of their zones are now known to be present in higher or lower zones.

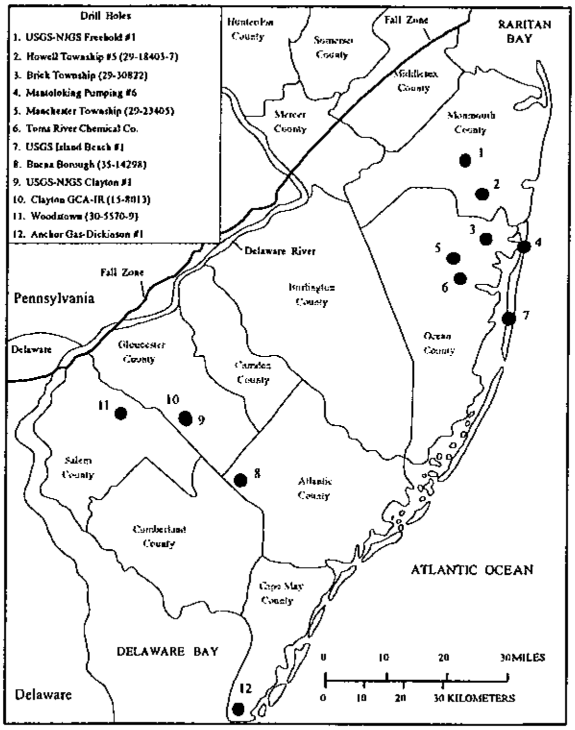


Figure 1. Map of the New Jersey Coastal Plain showing the approximate locations of drill holes discussed in this report. State permit numbers (in parentheses) are listed, where known, for water wells.

The ostracode interval zones of Hazel and Brouwers (1982) provide greater stratigraphic resolution for the Coniacian through Maastrichtian Stages (7 zones). These zones can be difficult to apply to the New Jersey section, however, because some marker species are scarce or absent and numerous species' ranges are attenuated due to common vertical changes in sedimentary facies and biofacies and to the erosion of sections along unconformities.

This report defines six informal ostracode zones (and nine subzones) for the Cretaceous calcareous marine sections of the New Jersey Coastal Plain. The distributions of selected well-described and taxonomically stable ostracode species in 10 New Jersey coreholes (fig. 1) provide the basis for this work (Gohn, 1992a, b). This provincial zonation is intended only for use in New Jersey and adjacent parts of the northern Atlantic Coastal Plain.

Acknowledgments. David Mason of the U.S. Geological Survey (USGS) ably operated the scanning electron microscope for this project. Samples from drill holes 2, 3, 5, 8, 10, and 11 (fig. 1) were provided by the New Jersey Geological Survey (NJGS). The drilling of the Freehold and Clayton coreholes was a cooperative venture of the NJGS and the USGS. Laurel M. Bybell (USGS) and Harry J. Dowsett (USGS) provided useful reviews of the manuscript.

CRETACEOUS LITHOSTRATIGRAPHY

Cenomanian, Turonian, Coniacian, and Santonian Sediments

Formations in the older part of the Upper Cretaceous section consist primarily of fluvial and marginal-marine beds; marine beds are present only in certain intervals (Owens and Sohl, 1969; Owens and others, 1977). These older sediments are assigned (from base to top) to the uppermost part of the Potomac Formation (Cenomanian), the Raritan Formation (Cenomanian), the Bass River Formation (Cenomanian and Turonian?), the Magothy Formation (Santonian), and a unit informally referred to herein as the Cheesequake beds (Santonian to Campanian), following the discussion in Litwin and others (1993). Biostratigraphic studies of the nonmarine and marginal-marine parts of these units primarily are limited to palynologic analyses (Doyle and Robbins, 1977; Christopher, 1979; Litwin and others, 1993).

The marine intervals in the pre-Campanian section include the subsurface upper part of the Potomac Formation in downdip areas only (Olsson, 1989), the outcropping Woodbridge Clay Member of the Raritan Formation and its downdip equivalent, the Bass River Formation (Petters, 1976), the outcropping Cliffwood beds at the top of the Magothy Formation, and the outcropping Cheesequake beds above the Magothy (Litwin and others, 1993). Ostracodes have never been reported from the upper part of the Potomac Formation or the Cliffwood and Cheesequake beds. Ostracodes also are unknown from the Woodbridge Clay Member outcrops but have been reported from subsurface Bass River sections (Brown and others, 1972).

Campanian and Maastrichtian Sediments

The Campanian and Maastrichtian sections consist of cyclic repetitions of clayey glauconite (or glauconite-quartz) sand, micaceous clay-silt, and quartz sand (Owens and Sohl, 1969; Owens and others, 1977).

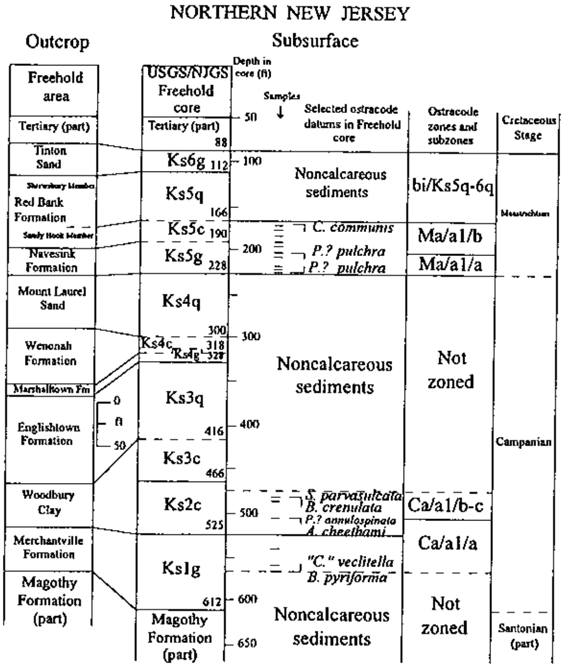


Figure 2. Stratigraphic sections for the Cretaceous outcrop belt and the USGS-NJGS Freehold #1 corehole in northern New Jersey. Informal lithologic units, informal ostracode zones, and selected ostracode datums are shown for the Campanian and Maastrichtian section in the Freehold core. The stratigraphy and unit thicknesses (shown as approximate maximum values) for the outcrop section are from Sugarman and others (1991) and Owens and others (1977).

In northern New Jersey, where the section is most complete, four cycles are traditionally recognized in the Cretaceous outcrop belt (fig. 2). The lowest cycle, which consists of the Merchantville Formation, the Woodbury Clay, and the Englishtown Formation, is succeeded upward by a cycle consisting of the Marshalltown and Wenonah Formations and the Mount Laurel Sand. The third cycle consists of the Navesink and Red Bank Formations and is succeeded by a truncated cycle at the top of the Cretaceous section that consists of the Tinton Sand.

In the subsurface, similar sediment patterns occur, but more cycles are present and their distributions are more complex. Gohn (1992a) recognized six subsurface Campanian and Maastrichtian cycles that he designated as cycles S1 through S6. These informal units are redesignated herein as units Ks1 through Ks6; some of these units are divided locally into subunits on the basis of lithology. The subunits carry lithologic modifiers (glauconite sand, clay-silt, quartz sand) attached to their designations; for example, Ks3q is a quartz-sand subunit in unit Ks3.

Correlation of the subsurface units with the traditional outcrop cycles (groups of formations and members) is not straightforward in all cases. The traditional cycle boundaries are transgressive marine unconformities that tend to bevel underlying cycles in the updip direction and (in New Jersey) from north to south. As a result, nearshore-marine sands are absent from some outcrop cycles and subsurface units due to down-from-the-top erosion. Where a quartz sand is missing at the top of a cycle and the overlying basal glauconite sand of the next cycle is thin, amalgamated or nearly amalgamated clay-silt subsurface units are produced that may be grouped into a single outcrop unit. Units Ks2 and Ks3 constitute one such case (fig. 2, 3).

An additional factor that may inhibit correlation of the Campanian and Maastrichtian units is the possibility that certain marginal-marine, sand-dominated sections represent low-stand, incised-valley-fill sections rather than high-stand delta-plain deposits, as traditionally interpreted. The concept of significant erosion along the bottoms of incised valleys (and subsequent valley filling) is largely uninvestigated in the New Jersey Cretaceous section. The coarse sands of the Englishtown Formation in northern New Jersey, which contrast with finer grained Englishtown marine sediments in southern New Jersey and Delaware (Owens and others, 1977), and the Shrewsbury Member of the Red Bank Formation are possible candidates for valley-fill sections.

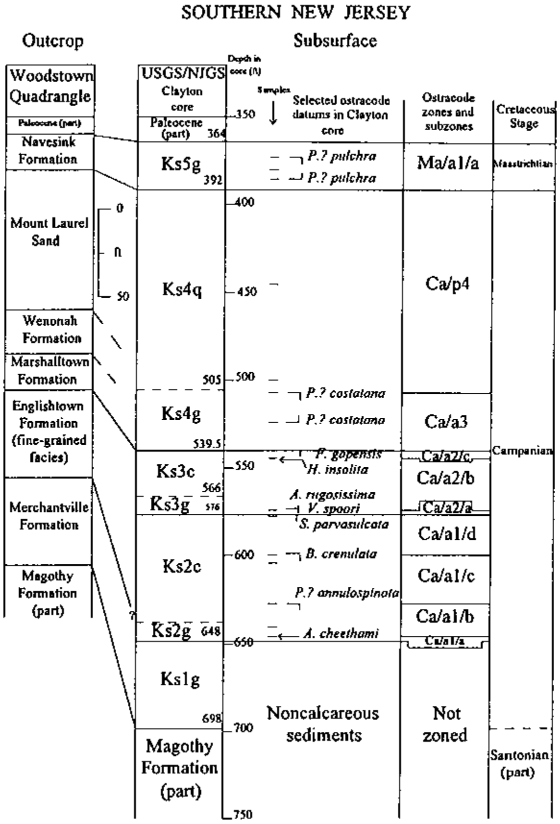


Figure 3. Stratigraphic sections for the Cretaceous outcrop belt and the USGS-Clayton #1 corehole in southern New Jersey. Informal lithologic units, informal ostracode zones, and selected ostracode datums are shown for the Campanian and Maastrichtian section in the Clayton #1 core. The stratigraphy and unit thicknesses (shown as approximate maximum values) for the outcrop section are from Minard (1965) and Owens and others (1977).

CRETACEOUS OSTRACODE BIOSTRATIGRAPHY

Zonation

Three types of biozones are used for the New Jersey ostracode zonation. The sole Cenomanian zone is an informal taxon range zone defined by the lowest and highest occurrences of a single species. Four informal ostracode assemblage zones and one informal ostracode partial-range zone are defined for the cyclic Campanian and Maastrichtian sediments. The assemblage zones are actually concurrent range zones (Oppel zones) whose upper and lower boundaries are defined by multiple taxa (NACSN, 1983, Art. 51(b)2). The partial range zone represents part of the range of a selected species as partitioned by the highest occurrence of a second species (lower zonal boundary) and the lowest occurrence of a third species (upper zonal boundary). The distributions of the Campanian and Maastrichtian zones and subzones in three representative New Jersey drill holes are shown in figures 2, 3, and 4. Within widely sampled intervals, the zone boundaries are drawn to coincide with major lithostratigraphic contacts.

The ostracode zones have alpha-numeric designations that describe their age (Cenomanian, Campanian, Maastrichtian), type (taxon range zone, assemblage zone, partial range zone), and position within a Stage (numbered consecutively from oldest to youngest). Hence assemblage zone Ca/a1 is the oldest Campanian zone. Subzones are labeled alphabetically from oldest to youngest within their zone; hence subzone Ca/a1/b is the second-oldest subzone in zone Ca/a1.

Noncalcareous sections. Cretaceous sections in New Jersey that lack calcareous fossil assemblages, including ostracodes, fall into one of two categories. The first category consists of marginal-marine deposits that originally contained little or no calcareous fossil material at their time of deposition. The outcropping upper part of the Potomac Formation, part of the Raritan Formation, the Magothy Formation, the coarse-grained facies of the Englishtown Formation in northern New Jersey (equals unit Ks3q), and the Shrewsbury Member of the Red Bank Formation (equals unit Ks5q) are typical examples of this category. These units are placed in barren interzones (NACSN, 1983, Art. 50(b)) because they have never yielded ostracode assemblages. Nomenclature for the barren interzones is derived from the informal

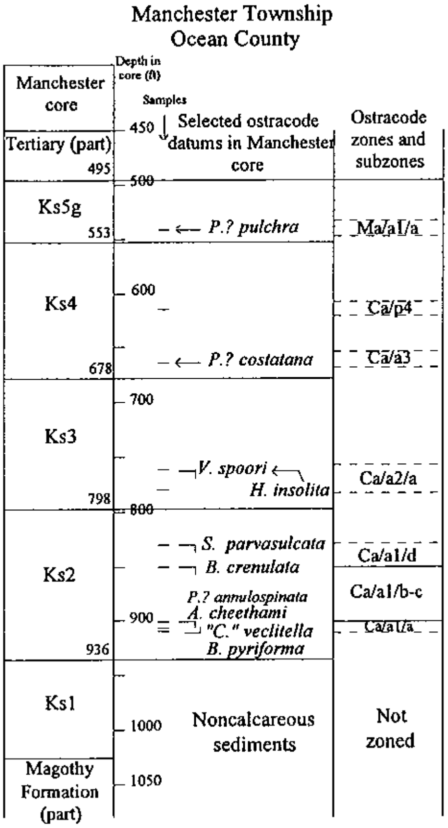


Figure 4. Informal lithologic units, informal ostracode zones, and selected ostracode datums are shown for the Campanian and Maastrichtian section in the Manchester Township drill hole (Ocean County).

subsurface stratigraphic units; for example, the Englishtown Formation (equals subunit Ks3q) of northern New Jersey may be assigned to barren interzone bi/Ks3q.

The second category consists of marine sections that lost their primary calcareous material through diagenetic alteration, presumably due to groundwater leaching in most cases. These units are typically burrowed and glauconite-bearing, and they may contain common molds of marine molluscs. Because of their obvious marine origin, these barren sections of otherwise calcareous units are simply referred to as unzoned intervals. Units Ks3 and Ks4 in the Freehold core (fig. 2) are examples of this type of section.

The following paragraphs define and describe the New Jersey ostracode zones. Statements of ages and comparisons to the regional zonations of Brown and others (1972) and Hazel and Brouwers (1982) also are listed. The original designations and present nomenclature of the ostracodes mentioned in this report are listed in table 1.

Cenomanian Zone

Ostracode range zone Ce/t1

Definition. Informal zone Ce/t1 is the taxon range zone of *Rehacythereis*? *eaglefordensis*. No subzones are defined for this zone.

Additional taxa. *Curfsina*? *fredericksburgoides*, *Paracyprideis*? *graysonensis s.l.*, and the punctate species *Cytherella beyrichoides* occur with *R.*? *eaglefordensis* in the studied sections.

Age and correlation with regional ostracode zones. Hazel (1969) and Carey (1992) reported *R.*? *eaglefordensis* from Cretaceous sections of the Western Interior assigned to the uppermost middle Cenomanian *Plesiacanthoceras wyomingense* Ammonite Zone through the upper Cenomanian *Sciponoceras gracile* Ammonite Zone. Cobban and Kennedy (1990) assign at least part of the outcropping Woodbridge Clay Member to the upper Cenomanian *Metoicoceras mosbyense* Ammonite Zone (immediately below the *S. gracile* Zone). *Rehacythereis? eaglefordensis* also occurs with the late Cenomanian planktic Foraminifera *Rotalipora cushmani* in the Western Interior (Carey, 1992) and northwestern Florida (Applin, 1955; Swain and Brown, 1964). *Rehacythereis*? *eaglefordensis* is a principal marker for the *Cythereis eaglefordensis-Cythereis fredericksburgoides* Assemblage Zone of Brown and others (1972).

New Jersey stratigraphy. Brown and others (1972) reported *R.*? *eaglefordensis* at approximately 2,145 ft in drill hole NJ-OC-T-1 (USGS-Island Beach #1, fig. 1) and at approximately 2,360 ft in drill hole NJ-CM-OT-1 (Anchor Gas-Dickinson #1). In wells studied for this report, *R.*? *eaglefordensis* is present at 1,333-1,336 ft in the Brick Township core and 1,522 ft in the Buena core.

Cenomanian to early Turonian ages have been assigned to the Bass River Formation in several New Jersey wells on the basis of calcareous nannofossils (Valentine, 1984) and planktic Foraminifera (Petters, 1976, 1977). However, *Rehacythereis*? *eaglefordensis* occurs near the middle of Petters' (1976) lower Turonian section in the Island Beach hole and near the top of the Turonian section in the Anchor Gas hole, thereby suggesting that at least part of the Turonian section is actually Cenomanian. Similarly, part of the Bass River section in the Toms River Chemical Company well (fig. 1) assigned by Valentine (1984, fig. 3) to the lower Turonian contains the Cenomanian calcareous nannofossil *Lithraphidites acutus*. No Turonian marine sediments in New Jersey are presently represented by described ostracode assemblages.

Table 1. Alphabetical list of original designations and present nomenclature for selected ostracode species found in the New Jersey Coastal Plain.

Original:	This report:
Brachycythere (B.) acuminata Hazel and Paulson, 1964	*Brachycythere acuminata* Hazel and Paulson, 1964
Orthonotacythere? annulospinata Hazel and Paulson, 1964	*Physocythere? annulospinata* (Hazel and Paulson, 1964)
Cythere arachoides Berry, 1925	*Veenia arachoides* (Berry, 1925)
Cytherella beyrichoides Swain and Brown, 1964	*Cytherella beyrichoides* Swain and Brown, 1964
Cythereis bicornis Israelsky, 1929	*"Cythereis" bicornis* Israelsky, 1929
Pterygocythereis (P.) cheethami Hazel and Paulson, 1964	*Alatacythere cheethami* (Hazel and Paulson, 1964)
Cythereis communis Israelsky, 1929	*Curfsina communis* (Israelsky, 1929)
Pterygocythereis (P.) compressa Hazel and Paulson, 1964	*Schizoptocythere? compressa* (Hazel and Paulson, 1964)
Cythereis costatana Israelsky, 1929	*Planileberis? costatana* (Israelsky, 1929)
Brachycythere sphenoides crenulata Crane, 1965	*Brachycythere crenulata* Crane, 1965
Cythereis curta Jennings, 1936	*Amphicytherura curta* (Jennings, 1936)
Cythereis eaglefordensis Alexander, 1929	*Rehacythereis? eaglefordensis* (Alexander, 1929)
Cytheridea everetti Berry, 1925	*Haplocytheridea everetti* (Berry, 1925)
Cytherella fabaformis Berry, 1925	*Antibythocypris fabaformis* (Berry, 1925)
Cythereis fredericksburgoides Swain and Brown, 1964	*Curfsina? fredericksburgoides* (Swain and Brown, 1964)
Cythere gapensis Alexander, 1929	*Fissocarinocythere gapensis* (Alexander, 1929)
Antibythocypris gooberi Jennings, 1936	*Antibythocypris gooberi* Jennings, 1936
Cytheridea graysonensis Alexander, 1929	*Paracyprideis? graysonensis* (Alexander, 1929)
Cythereis hannai Israelsky, 1929	*"Cythereis" hannai* Israelsky, 1929
Cythereis hazardi Israelsky, 1929	*Ascetoleberis hazardi* (Israelsky, 1929)
Cythere huntensis Alexander, 1929	*Fissocarinocythere huntensis* (Alexander, 1929)
Cytheridea insolita Alexander and Alexander, 1933	*Haplocytheridea insolita* (Alexander and Alexander, 1933)
Cytherideis minutus Berry, 1925	*Antibythocypris minuta* (Berry, 1925)
Xestoleberis opina Schmidt, 1948	*Xestoleberis opina* Schmidt, 1948
Cythereis ovatus Berry, 1925	*Brachycythere ovata* (Berry, 1925)
Cythereis ozanana Israelsky, 1929	*Veenia ozanana* (Israselsky, 1929)
Cytheridea (Haplocytheridea) paravasulcata Swain, 1948	*Schuleridea parvasulcata* (Swain, 1948)
Cytheridea pinochii Jennings, 1936	*Escharacytheridea pinochii* (Jennings, 1936)
Cythereis pittensis Swain and Brown, 1964	*Fissocarinocythere pittensis* (Swain and Brown, 1964)
Cythereis pulchra Jennings, 1936	*Planileberis? pulchra* (Jennings, 1936)
Cytheridea punctilifera Jennings, 1936	*Antibythocypris punctilifera* (Jennings, 1936)
Brachycythere (B.) pyriforma Hazel and Paulson, 1964	*Brachycythere pyriforma* Hazel and Paulson 1964
Cythereis reesidei Swain, 1948	*Mosaeleberis? reesidei* (Swain, 1948)
Pseudocythereis reticulata Jennings, 1936	*Anticythereis reticulata* (Jennings, 1936)
Cythere rhomboidalis Berry, 1925	*Brachycythere rhomboidalis* (Berry, 1925)
Cythereis rugosissima Alexander, 1929	*Ascetoleberis rugosissima* (Alexander, 1929)
Cythereis spoori Israelsky, 1929	*Veenia spoori* (Israelsky, 1929)
Cythereis bicornis veclitella Crane, 1965	*"Cythereis" veclitella* Crane, 1965
Cythereis verricula Butler and Jones, 1957	*Limburgina verricula* (Butler and Jones, 1957)
Cythereis magnifica Nine, 1954 [*nomen nudum*]	*"Cythereis"* new species 1

Campanian and Maastrichtian Zones

Ostracode assemblage zone Ca/a1

Definition. The base of assemblage zone Ca/a1 is defined by the lowest occurrence of *"Cythereis" veclitella* and (or) *Brachycythere pyriforma*. In practice, this boundary typically equates with the lowest ostracode-bearing sediments above the top of the Magothy Formation. The top of this zone is defined by the highest occurrence of species of the genus *Schuleridea* Swartz and Swain, 1946, *Schizoptocythere*? *compressa*, and (or) *Fissocarinocythere pittensis*.

Subzone definitions. Within zone Ca/a1, four subzones are recognized on the basis of the sequential highest occurrences (HO) (from older to younger) of *Alatacythere cheethami*, *Physocythere*? *annulospinata*, and *Brachycythere crenulata*. Subzone Ca/a1/a extends from the base of the zone to the HO of *A. cheethami*; subzone Ca/a1/b extends from the HO of *A. cheethami* to the HO of *P.*? *annulospinata*; subzone Ca/a1/c extends from the HO of *P.*? *annulospinata* to the HO of *B. crenulata*; and subzone Ca/o1/d extends from the HO of *B. crenulata* to the top of the zone.

Additional taxa. *Brachycythere* cf. *B. acuminata*, *"Cythereis" bicornis*, *"Cythereis" hannai*, and *Mosaeleberis*? *reesidei* are restricted to zone Ca/a1. *Antibythocypris gooberi*, *Antibythocypris minuta*, and *Veenia spoori* have their lowest occurrences in the upper part of this zone.

Age and correlation with regional ostracode zones. Bukry (1990) studied calcareous nannofossils from zone Ca/a1 in the Clayton core (fig. 3). He reported *Broinsonia parca parca* with *Marthasterites furcatus* throughout unit Ks1g; these species define the early Campanian calcareous nannofossil zone CC18. From the base of unit Ks2 to the highest studied sample at 610.5 ft, *B. parca parca* is present without *M. furcatus* (or *Ceratolithoides aculeus*); this distribution of nannofossils defines early Campanian zone CC19. The presence of *Alatacythere cheethami* in the lower part of zone Ca/a1 and *Antibythocypris* spp. with *Schizoptocythere*? *compressa*, *Schuleridea* spp., and others in the upper part of zone Ca/a1 places this interval in the chronozones of the *Alatacythere cheethami* Zone and the lower part of the *Ascetoleberis plummeri* Zone of Hazel and Brouwers (1982). These formal interval zones are early Campanian in age. Zone Ca/a1 is probably chronostratigraphically equivalent to part of the *Brachycythere* cf. *B. sphenoides*-*Cythereis quadrialira* Concurrent-Range Zone of Brown and others (1972). The large palmate Foraminifera *Kyphopyxa christneri* is frequently encountered in ostracode samples from zone Ca/a1.

New Jersey stratigraphy. Zone Ca/a1 is present in subsurface units Ks1 and Ks2 in the studied wells. Subunit Ks1g, and perhaps subunit Ks2g, are approximately equivalent to the outcropping Merchantville Formation, whereas subunit Ks2c is equivalent to all or part of the outcropping Woodbury Clay in northern New Jersey (fig. 2) and all or part of the outcrop section variously assigned to the Englishtown Formation (Minard, 1965) or the Woodbury Clay (Owens and others, 1977) in southern New Jersey (fig. 3). Zone Ca/a1 also is present in the Manchester Township well (fig. 4) and the Mantoloking #6, Island Beach #1, Howell Township #5, and Clayton GCA-IR drill holes discussed by Gohn (1992b, early Campanian sections).

Ostracode assemblage zone Ca/a2

Definition. The base of assemblage zone Ca/a2 is defined by the lowest occurrence(s) of *Haplocytheridea insolita* and (or) *Ascetoleberis rugosissima*. The top of the zone is defined by the highest occurrence of *Fissocarinocythere gapensis*, or in the absence of *F. gapensis*, at a slightly lower position by the highest occurrence of *H. insolita*. Zone Ca/a2 and overlying zone Ca/a3 have relatively few species in common, suggesting a substantial unconformity between these two zones.

Subzone definitions. Assemblage zone Ca/a2 is divided into three subzones by the highest occurrences of *Veenia spoori* and *Haplocytheridea insolita*. Subzone Ca/a2/a contains *V. spoori* and *H. insolita;* subzone Ca/a2/b lacks *V. spoori* but contains *H. insolita* and (rarely) *F. gapensis*; subzone Ca/a2/c lacks *V. spoori* and *H. insolita* but contains *F. gapensis*.

Additional taxa. Although assemblages from zone Ca/a2 are typically diverse, relatively few additional described species are present (Gohn, 1992b, sections identified as middle Campanian). Specimens assigned to *Brachycythere pyriforma* or *B.* cf. *B. pyriforma* are moderately common; *Veenia ozanana* is rare in the lower part of the zone.

Age and correlation with regional ostracode zones. Although present, planktic fossils have not been described from the sections of zone Ca/a2 studied for this report. The presence of *Ascetoleberis rugosissima* and the absence of *Fissocarinocythere pittensis* and *Schuleridea* spp., indicate a correlation of zone Ca/a2 with the chronozone of the upper part of the *Ascetoleberis plummeri* Interval Zone of Hazel and Brouwers (1982). This interval is middle Campanian in age. Zone Ca/a2 probably is chronostratigraphically equivalent to part of the *Brachycythere* cf. *B. sphenoides*-*Cythereis quadrialira* Concurrent-Range Zone of Brown and others (1972).

New Jersey stratigraphy. The boundaries of assemblage zone Ca/a2 are virtually coincident with the boundaries of subsurface unit Ks3. In southern New Jersey (fig. 3), this marine unit may correlate with part of the fine-grained Englishtown Formation. Zone Ca/a2 is also found in unit Ks3 in the Manchester core (fig. 4) and in one additional well (Mantoloking Pumping Station #6) studied by Gohn (1992a, b). Unit Ks3 is noncalcareous (leached) in the Freehold core (fig. 2), although subunit Ks3c in that section is obviously of marine origin.

Ostracode assemblage zone Ca/a3

Definition. The base of assemblage zone Ca/a3 is defined by the lowest occurrence(s) of *Antibythocypris punctilifera*, *Curfsina communis*, *Limburgina verricula*, *Planileberis*? *costatana*, *Xestoleberis opina*, and a substantial number of other late Campanian to Maastrichtian species. The top of the zone is defined by the highest occurrence of *P.*? *costatana*. No subzones are defined for zone Ca/a3. Functionally, zone Ca/a3 is equivalent to the total range of *P.*? *costatana*.

Additional taxa. In addition to the species listed in the definition, *Amphicytherura curta*, *Antibythocypris gooberi*, *Anticythereis reticulata*, *Escharacytheridea pinochii*, and *Fissocarinocythere huntensis* are common in zone Ca/a3.

Age and correlation with regional ostracode zones. In the Clayton core (fig. 3), the section assigned to zone Ca/a3 is placed in undifferentiated calcareous nannofossil zones CC20/21 (Sugarman and others, 1995, fig. 12). These authors considered this interval to be late Campanian in age. The presence of *Escharacytheridea pinochii* requires that zone Ca/a3 be no older than the *Escharacytheridea pinochii* Zone of Hazel and Brouwers (1982). Zone Ca/a3 is chronostratigraphically equivalent to the lower part of the *Veenia arachoides-Brachycythere rhomboidalis* Concurrent Range Zone of Brown and others (1972).

New Jersey stratigraphy. Zone Ca/a3 is present in subsurface subunits Ks4g, Ks4c, and locally in the lower part of Ks4q. These units are equivalent to the outcropping Marshalltown and Wenonah Formations and the lower part of the Mount Laurel Sand. In addition to the illustrated drill holes, zone Ca/a3 is also present in the Woodstown and Howell Township #5 drill holes studied by Gohn (1992b).

Ostracode partial range zone Ca/p4

Definition. Partial range zone Ca/p4 is defined as that part of the range of *Curfsina communis* above the highest occurrence of *Planileberis? costatana* and below the lowest occurrence of *Planileberis? pulchra.*

Additional taxa. Most of the described species found in zone Ca/a3 and in subzone Ma/a1/a (see below) are also present in zone Ca/p4. Exceptions are listed in the discussions of these other zones. Some samples from this zone contain large percentages of smooth-valved species representing several genera.

Age and correlation with regional ostracode zones. The interval assigned to zone Ca/p4 in the Clayton core (fig. 3) is also assigned to calcareous nannofossil zone CC22 (Sugarman and others, 1995, fig. 12). Following Burnett and others (1992), Sugarman and others (1995) placed the Campanian-Maastrichtian Stage boundary in calcareous nannofossil zone CC23a. Hence, in New Jersey, where zone CC25 in the Navesink Formation typically rests on zone CC22 in the Mount Laurel Sand, the Stage boundary coincides with the Navesink-Mount Laurel contact (Sugarman and others, 1995) and with the equivalent contact between subsurface units Ks4 and Ks5. Zone Ca/p4 probably is chronostratigraphically equivalent to the lower part of the *Platycosta lixula* Interval Zone of Pitakpaivan and Hazel (1994) and part of the *Veenia arachoides-Brachycythere rhomboidalis* Concurrent-Range Zone of Brown and others (1972).

New Jersey stratigraphy. Partial-range zone Ca/p4 is present in the middle and upper parts of the Mount Laurel Sand and locally in the lower part of that unit (fig. 3). This interval is equivalent to subsurface subunit Ks4q. Many samples from this interval, particularly the coarser sands, are barren or contain poorly preserved assemblages. Zone Ca/p4 is present in the Clayton and Manchester cores (figs. 3, 4) and in the Woodstown drill hole studied by Gohn (1992b).

Ostracode assemblage zone Ma/a1

Definition. The base of assemblage zone Ma/a1 is defined by the lowest occurrence(s) of *Planileberis*? *pulchra* and (or) *"Cythereis"* n. sp. 1. The top of the zone is defined by the highest occurrence of Cretaceous ostracodes, as typified by the highest occurrence of the common species *Curfsina communis* and *Haplocytheridea everetti*. *"Cythereis"* n. sp. 1 is the form assigned to *Cythereis magnifica* in the unpublished thesis of Nine (1954).

Subzone definitions. Zone Ma/a1 is divided into two subzones by the highest occurrence of *Planileberis*? *pulchra*. Sections containing *P.*? *pulchra* are assigned to subzone Ma/a1/a and overlying sections that lack this species are assigned to subzone Ma/a1/b.

Additional taxa. In some studied sections, the highest occurrence of *Limburgina verricula* is only slightly lower than that of *P.*? *pulchra*; hence the highest occurrence of *L. verricula* can be used to approximate the subzone boundary. *Ascetoleberis hazardi* appears to be restricted to zone Ma/a1 in New Jersey.

High species diversity and specimen abundance are typical of the assemblages in zone Ma/a1. In addition to the species named in the zonal definitions and numerous undescribed species, the most common described taxa are *Amphicytherura curta*, *Antibythocypris fabaformis*, *A. gooberi*, *A. punctilifera*, *Anticythereis reticulata*, *Brachycythere ovata*, *B. rhomboidalis*, *Escharacytheridea pinochii*, *Fissocarinocythere huntensis*, *Veenia arachoides*, and *Xestoleberis opina*. More complete species lists that represent this zone are given in Jennings (1936, Navesink Formation samples), Adams (1960, Red Bank Formation samples), and Gohn (1992a, b; middle to late Maastrichtian samples), and in the unpublished thesis by Nine (1954).

Age and correlation with regional ostracode zones. C.C. Smith (*in* Owens and others, 1977, figs. 91, 92) described diverse foraminiferal assemblages from sections of the Navesink Formation and the Sandy Hook Member of the Red Bank Formation exposed at the well-known Poricy Brook and Big Brook localities in Monmouth County (Olsson, 1987). Ostracodes (this report) and calcareous nannofossils (S. Moshkovitz, *in* Sugarman and others, 1995, fig. 14) from splits of Smith's samples also have been examined. *Planileberis*? *pulchra* is present in all ostracode-bearing samples from these outcrops except the highest sample in the Sandy Hook Member. With regard to the planktic Foraminifera, *Gansserina gansseri* is present at the base of the interval containing *P.*? *pulchra*, and *Rosita contusa* and *Racemiguembelina fructicosa* have their lowest occurrences within the range of *P.*? *pulchra*. In addition, the lowest occurrences of the calcareous nannofossils *Lithraphidites quadratus* and *Nephrolithus frequens* are within the range of *P.*? *pulchra* at these exposures. The presence of these Maastrichtian planktic species within ostracode assemblage subzone Ma/a1/a defines a Maastrichtian age for both subzones of assemblage zone Ma/a1.

Ostracode interval zones defined by Hazel and Brouwers (1982) and Pitakpaivan and Hazel (1994) are difficult to apply to the New Jersey section because most of the important marker species are absent. However, the planktic species described above indicate a biochronostratigraphic correlation of assemblage zone Ma/a1 to the upper part of the *Platycosta lixula* Interval Zone and the overlying *Veenia parallelopora* Interval Zone of Pitakpaivan and Hazel (1994). Several of the species in zone Ma/a1 are primary markers for the *Veenia arachoides* - *Brachycythere rhomboidalis* Concurrent-Range Zone of Brown and others (1972, p. 45).

New Jersey stratigraphy. In northern New Jersey, zone Ma/a1 is virtually coincident with the combined sections of the Navesink Formation (equals subunit Ks5g) and the Sandy Hook Member (equals subunit Ks5c) of the Red Bank Formation (fig. 2). Most of the Navesink section contains *Planileberis? pulchra* and is assigned to subzone Ma/a1/a. The Sandy Hook Member, and the broadly gradational contact interval between the Navesink Formation and the Sandy Hook Member, are assigned to subzone Ma/a1/b. At Poricy Brook (see previous section), *P.*? *pulchra* is present slightly higher within the Navesink-Sandy Hook transition interval.

In southern New Jersey and downdip areas toward the Atlantic coast, the Red Bank Formation and Tinton Sand (subunits Ks5c, Ks5q, and Ks6g) are absent, and glauconitic sediments of the Navesink Formation (subunit Ks5g) are present directly below Tertiary sediments. These downdip Ks5g sections invariably contain *P.*? *pulchra* and are assigned to subzone Ma/a1/a (figs. 3, 4). Zone Ma/a1 also is present in the Howell Township #5 and Island Beach #1 drill holes (Gohn, 1992b).

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PLATE I

[Scale bar = 100 microns]

Figures. 1. *Planileberis*? *pulchra* (Jennings, 1936). Female right valve. Freehold core, 203 ft.

2. *Planileberis*? *costatana* (Israelsky, 1929). Female left valve. Clayton core, 507.5 ft.
3. *"Cythereis"* new species 1. Left valve. Big Brook, sample 3G.
4. *Rehacythereis*? *eaglefordensis* (Alexander, 1929). Female right valve. Brick Township core, 1,333-1,336 ft.
5. *Curfsina communis* (Israelsky, 1929). Female right valve. Poricy Brook, sample 4E.
6. *"Cythereis" hannai* Israelsky, 1929. Female left valve. Freehold core, 488 ft.
7. *"Cythereis" bicornis* Israelsky, 1929. Female left valve. Manchester core, 901 ft.
8. *"Cythereis" veclitella* Crane, 1965. Female left valve. Manchester core, 910 ft.
9. *Mosaeleberis*? *reesidei* (Swain, 1948). Female left valve. Manchester core, 910 ft.
10. *Limburgina verricula* (Butler and Jones, 1957). Female right valve. Howell Township core, 382 ft.

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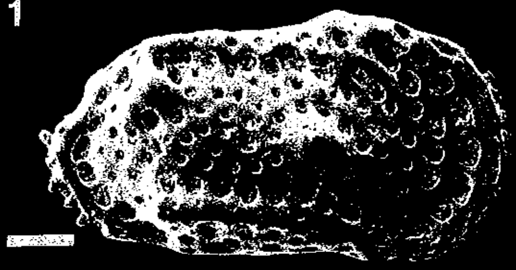

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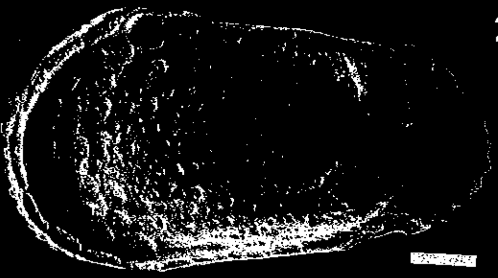

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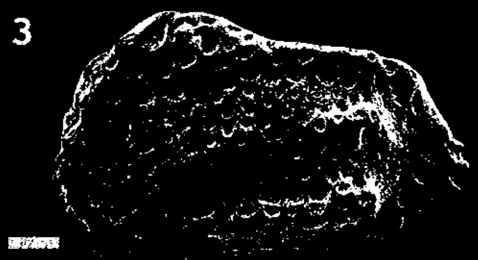

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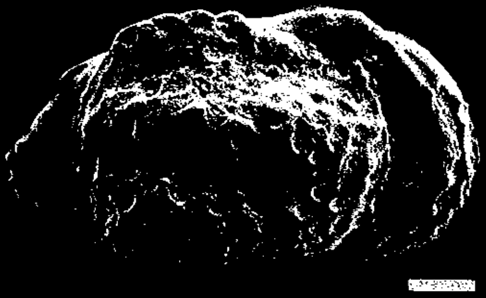

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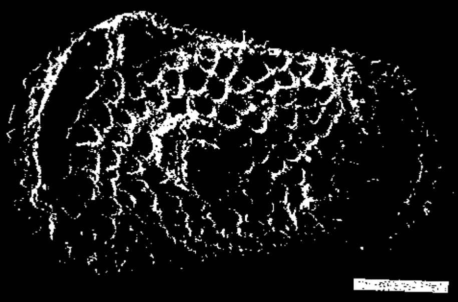

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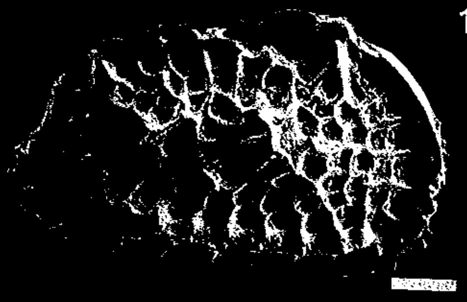

PLATE II

[Scale bar = 100 microns]

Figures. 1. *Brachycythere rhomboidalis* (Berry, 1925). Female left valve. Poricy Brook, sample 4B.

2. *Brachycythere ovata* (Berry, 1925). Female left valve. Poricy Brook, sample 4A.

3. *Brachycythere crenulata* Crane, 1965. Female left valve. Freehold core, 482 ft.

4. *Brachycythere pyriforma* Hazel and Paulson, 1964. Female left valve. Clayton core, 604 ft.

5. *Brachycythere* cf. *B. acuminata* Hazel and Paulson, 1964. Female carapace, left side. Mantoloking core, 1,027 ft.

6. *Alatacythere cheethami* (Hazel and Paulson, 1964). Female left valve. Manchester core, 910 ft.

7. *Schizoptocythere*? *compressa* (Hazel and Paulson, 1964). Left valve. Manchester core, 901 ft.

8. *Haplocytheridea insolita* (Alexander and Alexander, 1933). Female left valve. Clayton core, 544.5 ft.

9. *Antibythocypris fabaformis* (Berry, 1925). Female left valve. Poricy Brook, sample 4F.

10. *Antibythocypris gooberi* Jennings, 1936. Female right valve. Poricy Brook, sample 4F.

11. *Antibythocypris minuta* (Berry, 1925). Female right valve. Freehold core, 190 ft.

12. *Antibythocypris punctilifera* (Jennings, 1936). Female left valve. Manchester core, 541 ft.

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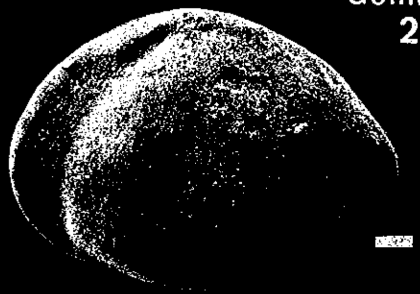

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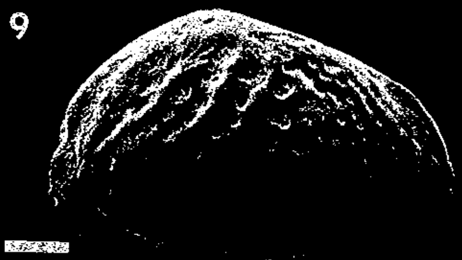

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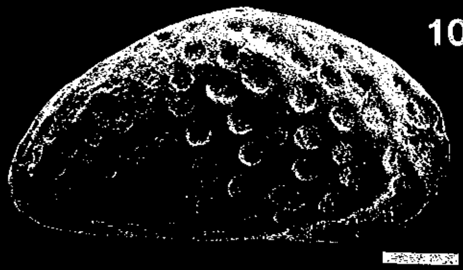

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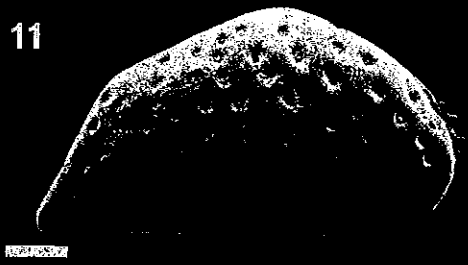

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PLATE III

[Scale bar = 100 microns]

Figures. 1. *Escharacytheridea pinochii* (Jennings, 1936). Female right valve. Freehold core, 203 ft.

2. *Schuleridea parvasulcata* (Swain, 1948). Female left valve. Freehold core, 488 ft.

3. *Fissocarinocythere gapensis* (Alexander, 1929). Female carapace, left side. Mantoloking core, 912 ft.

4. *Fissocarinocythere pittensis* (Swain and Brown, 1964). Female left valve. Manchester core, 850 ft.

5. *Veenia arachoides* (Berry, 1925). Female right valve. Poricy Brook, sample 4F.

6. *Veenia spoori* (Israelsky, 1929). Female left valve. Clayton core, 604 ft.

7. *Ascetoleberis hazardi* (Israelsky, 1929). Left valve. Poricy Brook, 4F.

8. *Ascetoleberis rugosissima* (Alexander, 1929). Right valve. Clayton core, 573 ft.

9. *Xestoleberis opina* Schmidt, 1948. Male left valve. Clayton core, 381.5 ft.

10. *Physocythere*? *annulospinata* (Hazel and Paulson, 1964). Right valve. Clayton core, 627 ft.

11. *Amphicytherura curta* (Jennings, 1936). Right valve. Poricy Brook, sample 4E.

12. *Anticythereis reticulata* (Jennings, 1936). Female left valve. Freehold core, 221.6 ft.

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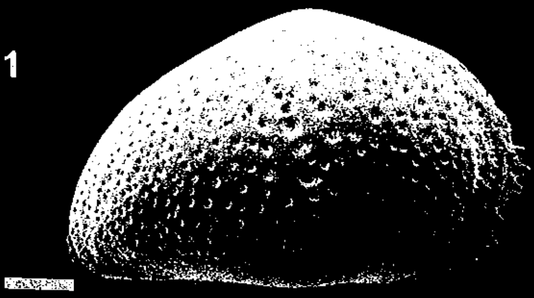

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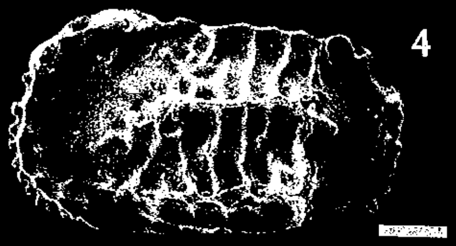

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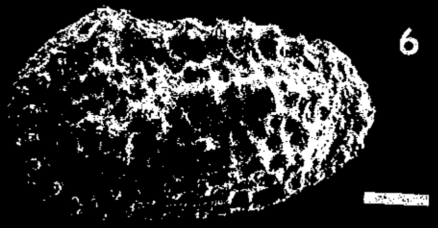

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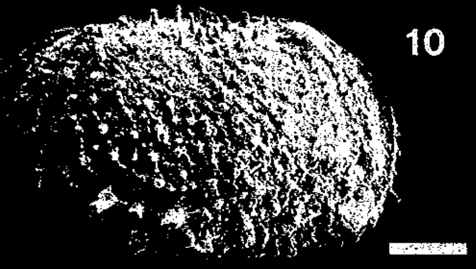

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Cretaceous and Paleogene Calcareous Nannofossil Biostratigraphy of New Jersey

By **Jean M. Self-Trail and Laurel M. Bybell** (U.S. Geological Survey, Reston, Va 22092)

ABSTRACT

Cretaceous and (or) Paleogene calcareous nannofossils from 27 coreholes in central and southern New Jersey were examined using light and scanning electron microscopes. Determinations of the biostratigraphic placement of lithologic units were based on first appearance and last appearance datums of formally designated calcareous nannofossil marker species combined with the authors' personal observations on the ranges of additional species. The validity of using certain Cretaceous cosmopolitan marker species (i.e., species in the *Quadrum* genus) in New Jersey is discussed along with their relationships to latitudinal variation and sea-surface temperature. Distributions and thicknesses of Paleogene calcareous nannofossil zones in subsurface units were determined. It was noted that coarsening and thickening of these units to the southeast relates directly to tectonic uplift and subsequent erosion of the Appalachian Mountains during the middle Oligocene. Several major unconformities in the Cretaceous and Paleogene were identified using the calcareous nannofossil data. Fossil data from New Jersey were compared to fossil data from sediments in Delaware, Maryland, Virginia, North Carolina, and South Carolina.

INTRODUCTION

As part of a joint U.S. Geological Survey-New Jersey Geological Survey mapping program begun in 1984, calcareous nannofossils were examined from 27 coreholes in central and southern New Jersey (fig. 1). Exposures of fossiliferous outcrop material in New Jersey are limited in extent due to extensive weathering and are therefore of limited use in interpreting the geologic history of the region. In order to better understand the geologic history of New Jersey, the authors examined samples from drillholes in which Cretaceous and Paleogene units are thicker and better preserved than in the outcropping updip sections.

There are few studies that deal primarily with the calcareous nannofossil biostratigraphy of New Jersey marine sediments. Valentine (1984) discussed the Cenomanian-Turonian calcareous nannofossil and pollen biostratigraphy of two drillholes (Toms River and Island Beach) in the New Jersey coastal plain. Bukry (1990) discussed Cretaceous marine sediments of southern New Jersey from several coreholes, and Miller et al. (1993) presented data for a short interval of upper Cretaceous sediments from a new core at Island Beach (fig. 1). Jiang and Wise (1987), Bybell (1992), and Bybell and Self-Trail (1995) dealt almost exclusively with calcareous nannofossils from sediments that cross the Paleocene-Eocene boundary. Poore and Bybell (1988) discussed Eocene to Miocene biostratigraphy of the ACGS-4 corehole, and Miller et al. (1993) discussed the Cenozoic history of the recently cored Island Beach and Atlantic City coreholes (fig. 1).

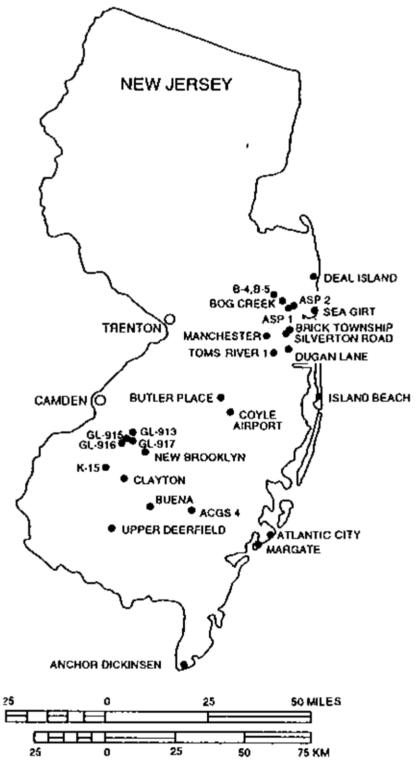


Figure 1. Locations of drillholes (solid circles) in New Jersey that are discussed in text.

Most studies dealing with New Jersey coastal plain sediments present the lithology and sequence stratigraphy of the marine sediments and use micropaleontological evidence as a tool for interpretation. Sugarman et al. (1995) used calcareous nannofossils to date the Upper Cretaceous sediments of New Jersey in a framework study. Two maps (Sugarman et al., 1991; Sugarman and Owens, 1994) used calcareous nannofossil zonal boundaries to help date sediments within three New Jersey quadrangles. These dates were then used to delineate the extent of marine sediments of Cretaceous through Tertiary age in the New Jersey coastal plain. Sequence stratigraphic studies and geologic studies focusing on Paleocene to Eocene age material that incorporate calcareous nannofossil biostratigraphy include Olsson and Wise (1987a; 1987b), Owens et al. (1988), Gibson et al. (1993), Gibson and Bybell (1995) and Browning et al. (in press). Miller et al. (1990) discussed sea-level changes on the New Jersey coastal plain in the Paleogene.

WHAT ARE CALCAREOUS NANNOFOSSILS?

Calcareous nannofossils are fossilized remains of coccolithophores, a group of unicellular, biflagellate, golden-brown marine algae. Modern coccolithophorids are photosynthesizers that live in the photic zone. They are placed in the kingdom Protista, and their ability to produce calcareous platelets appears to be light dependant. These calcareous platelets, which are produced in the golgi body, a netlike mass of material found in cell cytoplasm that is believed to aid in cellular secretion, are later extruded to cover the cell surface. The platelets often disarticulate upon death or following consumption of the cell by marine animals. They rain down on the sea floor, either separately or encased in fecal matter, where they become part of the sedimentary section. Platelets constructed of small uniform calcite crystals are called holococcoliths and typically fall apart easily upon death. Samples containing abundant intact holococcoliths are thought to represent excellent preservational conditions. More commonly, however, platelets are composed of heterococcoliths, which are constructed of variously shaped calcareous particles.

Calcareous nannofossil remains were first preserved in rocks of the Late Triassic (Norian) strata (Jafar, 1983). However, there is some debate as to when the actual appearance of these fossils first occurred. Noël (1961, 1965) illustrated what appear to be calcareous nannofossils from the Pennsylvanian of North America, and Pirini-Radrizzani (1971) illustrated coccoliths from the Permian of Turkey. Gartner and Gentile (1973) illustrated by transmission electron microscope (TEM) a form from the Pennsylvanian of North America that closely resembles the modern-day species *Emiliania huxleyi*, and this is thought by many to be a contaminant. It has been pointed out by many micropaleontologists that few, if any, unrecrystallized Paleozoic oceanic limestones exist on the continents today. If evolution of the coccolithophorids did indeed take place before the Triassic, virtually no record of this event would remain. As for the assumption that all calcareous nannofossil forms documented before the Triassic represent contaminants based on morphologic similarities, one has only to look at the Cretaceous form *Micula decussata* (pl. 1, figs. 6, 9-11) and compare it to the Eocene form *Rhomboaster bramlettei* (pl. 8, figs. 1-3, 6) to see that iterative evolution is a very real phenomenon.

METHODS

Sampling intervals varied from core to core and were based on amount and type of material present. Where possible, cores were sampled in the U.S. Geological Survey (USGS) calcareous nannofossil laboratory as soon as coring was complete. The preferred sampling interval was 5 to 10 ft. This was to ensure that samples were obtained from each unit and that each calcareous nannofossil zone was represented. Cores were resampled at closer intervals following preliminary examination of nannofossil slides if it was determined to be necessary. In some cases, however, it was not possible to sample core material directly after drilling. In these instances, residual drilling mud was carefully scraped off the core segment, and a clean sample was obtained from the central portion of a freshly broken core segment. All samples were dried in a convection oven to remove residual water, and the resultant sediment was stored in vials.

Smear slides were prepared using a timed settling procedure to obtain the correct size fraction. Cover slips were attached to the slides using Norland Optical Adhesive (NOA-65), a clear adhesive that bonds glass to glass and cures when exposed to ultraviolet radiation.

All samples, both Mesozoic and Cenozoic, were initially examined using a Zeiss Photomicroscope III. Samples thought to have the best preservation and the highest abundances of calcareous nannofossils were later scanned using a JEOL 135 scanning electron microscope (SEM) in order to obtain more detailed taxonomic information.

BIOSTRATIGRAPHY OF CRETACEOUS SEDIMENTARY UNITS

Few studies have been published on calcareous nannofossils from Cretaceous sediments of New Jersey because of the paucity of available material. However, recent cooperative drilling by the U.S. Geological Survey and the New Jersey Geological Survey, as part of a project to map the subsurface formations and aquifers of the state, has provided a wealth of material for calcareous nannofossil study. In the following sections, biostratigraphic ages are based primarily on the zonation of Perch-Nielsen (1985a). Personal commentaries on the diachronous nature of some species ranges or remarks on latitudinal paleotemperature control of species distributions are based on the authors' observations made in comparing the biostratigraphy of sediments in New Jersey to age-equivalent sediments in South Carolina. The difficulties in placement of the Campanian-Maastrichtian boundary, as pointed out by Burnett et al. (1992) and Sugarman et al. (1995), are discussed below.

Table 1 lists the calcareous nannofossil species used to date the Cretaceous sediments in New Jersey. Identifications of species used to define zonal boundaries are based on Perch-Nielsen (1985a). The authors have found the remaining species in the table to be biostratigraphically useful in the Atlantic Coastal Plain. First appearance datums (FAD's) and last appearance datums (LAD's) of species can be placed inside a particular calcareous nannofossil zone with a high degree of accuracy.

Bass River Formation

Zone CC 10b; late Cenomanian

The Bass River Formation is the oldest Upper Cretaceous unit that contains calcareous nannofossils in New Jersey. Sections of this formation typically consist of interstratified light-colored sands and dark clayey strata. This unit is missing in updip areas due to erosion and is not present in New Jersey, Delaware or Maryland as outcrop material. The age-equivalent Raritan Formation crops out in northern New Jersey, but only rarely has it yielded dateable marine material (Cobban and Kennedy, 1990). Perry et al. (1975) reported a latest Cenomanian to earliest Turonian age (Palynozone IV) based on the presence of palynomorphs and Valentine (1984) assigned a Turonian age to this unit based on the presence of the calcareous nannofossil species *Lithraphidites acutus* and *Corollithion achylosum*. The authors assign a latest Cenomanian age (Subzone CC 10b) to this unit based on calcareous nannofossils.

Four samples that were examined from the Brick Township corehole (1340, 1333, 1305, and 1290 ft) in east-central New Jersey (fig. 1) contain the calcareous nannofossil species *Microrhabdulus decoratus*, *Eiffellithus turriseiffelii*, and *Axopodorhabdus albianus*. The FAD of *E. turriseiffelii* marks the base of Zone CC 9, whereas the FAD of *M. decoratus* indicates that these samples can be no older than Zone CC 10, or latest Cenomanian. The presence of *A. albianus*, which has its LAD at the top of the Cenomanian, also places these samples within Zone CC 10. The absence of *Microstaurus chiastius*, whose LAD marks the top of Subzone CC 10a and the base of Subzone CC 10b, further corroborates assignment to Subzone CC 10b. The FAD of *Quadrum gartneri*, which defines the base of Zone CC 11 and the base of the Turonian, is not present in any of these samples.

Samples at 1350 and 1320 ft in the Buena corehole in southern New Jersey (fig. 1) also contain late Cenomanian calcareous nannofossils. Like the Brick Township core, the Buena samples are no older than Subzone CC 10b, based on the presence of *Microrhabdulus belgicus* and *Corollithion exiguum*, both of which have their FAD's at the base of Zone CC 10b, and the absence of *Microstaurus chiastius* (LAD at the top of Subzone CC 10a). The absence of *Quadrum gartneri* (FAD marks the base of CC 11) further corroborates an age of Zone CC 10b. There have been no Cenomanian calcareous nannofossils reported from other New Jersey samples to date.

Merchantville Formation

Subzone CC 18a, Subzone 18c
early Campanian

The Merchantville Formation is the oldest coastal plain unit to contain large amounts of glauconite. It consists of clayey, glauconitic, quartz silts and sands and is typically fossiliferous and extensively bioturbated.

The authors examined Merchantville material from the Clayton corehole in southern New Jersey (fig. 1) and found a rich calcareous nannoflora. Samples from 664.0, 661.8, and 659.0 ft contain a flora indicative of calcareous nannofossil Subzone CC 18a (early Campanian). Bukry (1990) examined material from 701 to 673 ft in the Clayton corehole, and he questionably assigned this interval to Subzone

Table 1. Biostratigraphically useful Cretaceous calcareous nannofossil species. For Stages; e=early, l=late.

LAD or FAD	**Species Name**	**Perch-Nielsen zonation**	**Stage**
FAD	*Micula prinsii*	**base CC 26b**	l Maastrichtian
FAD	*Nephrolithus frequens*	**base CC 26a**	l Maastrichtian
FAD	*Ceratolithoides kamptneri*	**base CC 26a**	l Maastrichtian
LAD	*Micula praemurus*	in CC 25c	l Maastrichtian
FAD	*Micula murus*	**base CC 25c**	l Maastrichtian
FAD	*Lithraphidites grossopectinatus*	in CC 25b	l Maastrichtian
FAD	*Lithraphidites quadratus*	**base CC 25b**	l Maastrichtian
FAD	*Micula praemurus*	in CC 25a	l Maastrichtian
LAD	*Reinhardtites levis*	**top CC 24**	e Maastrichtian
LAD	*Tranolithus phacelosus*	**top CC 23b**	e Maastrichtian
LAD	*Quadrum trifidum*	**top CC 23b**	e Maastrichtian
LAD	*Prediscosphaera arkhangelskyi*	in CC 23b	e Maastrichtian
LAD	*Aspidolithus parcus parcus*	**top CC 23a**	e Maastrichtian
LAD	*Aspidolithus parcus constrictus*	**top CC 23a**	e Maastrichtian
LAD	*Reinhardtites anthophorus*	**top CC 22c**	l Campanian
LAD	*Eiffellithus eximius*	**top CC 22c**	l Campanian
LAD	*Hexalithus gardetae*	in CC 22c	l Campanian
FAD	*Reinhardtites levis*	**base CC 22c**	l Campanian
LAD	*Lithraphidites grillii*	**top CC 22a**	l Campanian
FAD	*Hexalithus gardetae*	in CC 22a	l Campanian
FAD	*Quadrum trifidum*	**base CC 22a**	l Campanian
FAD	*Quadrum sissinghii*	**base CC 21**	l Campanian
FAD	*Ceratolithoides aculeus*	**base CC 20**	e Campanian
LAD	*Calculithes ovalis*	top CC 19b	e Campanian
LAD	*Bukryaster hayi*	**top CC 19a**	e Campanian
LAD	*Marthasterites furcatus*	**top CC 18c**	e Campanian
FAD	*Ceratolithoides verbeekii*	**base CC 18c**	e Campanian
FAD	*Aspidolithus parcus constrictus*	**base CC 18c**	e Campanian
FAD	*Bukryaster hayi*	**base CC 18b**	e Campanian
FAD	*Aspidolithus parcus* cf. *constrictus*	**base CC 18b**	e Campanian
FAD	*Aspidolithus parcus*	**base CC 18a**	e Campanian
FAD	*Calculites obscurus*	**base CC 17**	e Campanian
LAD	*Eprolithus floralis*	**top CC 16**	l Santonian
FAD	*Lucianorhabdus cayeuxii*	**base CC 16**	l Santonian
LAD	*Lithastrinus septenarius*	**top CC 15**	e Santonian
FAD	*Reinhardtites anthophorus*	**base CC 15**	e Santonian
FAD	*Lithraphidites grilli*	**base CC 15**	e Santonian
FAD	*Micula concava*	**base CC 15**	e Santonian
FAD	*Micula decussata*	**base CC 14**	l Coniacian
FAD	*Calculites ovalis*	base CC 14	l Coniacian
FAD	*Lithastrinus septenarius*	**base CC 13b**	e Coniacian
FAD	*Marthasterites furcatus*	**base CC 13a**	e Coniacian
FAD	*Prediscosphaera arkhangelskyi*	base CC 13a	e Coniacian
FAD	*Eiffellithus eximius*	**base CC 12**	l Turonian
FAD	*Lucianorhabdus maleformis*	**base CC 12**	l Turonian
FAD	*Quadrum gartneri*	**base CC 11**	e Turonian
LAD	*Axopodorhabdus albianus*	in CC 10b	l Cenomanian
FAD	*Corollithion exiguum*	base CC 10b	l Cenomanian
FAD	*Microrhabdulus belgicus*	base CC 10b	l Cenomanian
LAD	*Microstaurius chiastius*	**top CC 10a**	l Cenomanian
FAD	*Microrhabdulus decoratus*	**base CC 10a**	l Cenomanian
FAD	*Lithraphidites acutus*	**base CC 10a**	l Cenomanian

CC 18a due to the presence of Eocene coccoliths mixed in with the Campanian flora. He reported, however, the occurrence of Subzone CC 18b from 668 to 649 ft based on the presence of *Aspidolithus* sp. cf. *A. parca constricta.* The current authors found no specimens of *Aspidolithus* sp. cf. *A. parca constricta* in these samples, but did find well-preserved specimens of *A. parcus parcus* s.l.

The base of Subzone CC 18b is defined by the FAD of *Aspidolithus parcus*, whereas the FAD of *Aspidolithus parcus* cf. *constrictus* defines the top of Subzone CC 18a and the base of Subzone CC 18b (along with the FAD of *Bukryaster hayi*). *Aspidolithus parcus* cf. *constrictus* and *B. hayi* were not identified by the authors, but *A. parcus*, along with *Marthasterites furcatus* are present at 664.0 to 659.0 ft. Both *B. hayi* and *A. parcus* cf. *constrictus* are often difficult to identify. This can result in a jump from Subzone CC 18a to Subzone CC 18c, the base of which is defined by the FAD's of *Aspidolithus parcus constrictus* and *Ceratolithoides verbeekii.*

Three samples that were examined from the Merchantville Formation in the Clayton core from 656.4 to 647 ft can be placed into calcareous nannofossil Subzone CC 18c. All three samples contain *Marthasterites furcatus*, as well as definite examples of *Aspidolithus parcus constrictus.* Neither Bukry (1990) nor the current authors report *Ceratolithoides verbeekii* from the Clayton core. Nannofossils are abundant and range from well preserved to moderately preserved in the Merchantville Formation. The presence of relatively abundant holococcoliths, which tend to disaggregate quickly in unfavorable conditions, also argues for good early preservation.

Englishtown Formation
Zone CC 19; late early Campanian

The Englishtown Formation consists primarily of unconsolidated, fine-to-coarse sand that contains thin-to-thick-bedded, dark carbonaceous, clay to silt (Owens et al., 1977; Houlik et al., 1983). Gregory Gohn (USGS, pers. commun., 1995) separates the lower Campanian section above the Merchantville Formation into two cycles in the Clayton core. The lower cycle consists predominantly of fine-grained sediments, whereas the upper cycle consists of a basal glauconite unit that grades upward into a more clayey unit.

Samples from the Englishtown Formation in the Clayton core contain a diverse and well preserved calcareous nannofossil flora. Samples from 642.2, 639.5, 637.4, 634.9, 632.1, and 628.0 ft belong to Zone CC 19 (early Campanian). Zone CC 19 is based on the absence, rather than the presence, of key calcareous nannofossils. Samples examined from this interval did not contain *Marthasterites furcatus*, whose LAD defines the top of Zone CC 18, nor did they contain *Ceratolithoides aculeus*, whose FAD marks the base of the Zone CC 20. Zone CC 19 was separated into two subzones (CC 19a and CC 19b) by Perch-Nielsen (1985a). She defined the top of Subzone CC 19a on the LAD of *Bukryaster hayi.* This species, however, is very small and is not found very often. Therefore, no attempt was made by the authors to subdivide this zone in the Clayton core. Bukry (1990) also reported Zone CC 19 from 645.5 to 610.5 ft in the Clayton core.

The authors also record the presence of Zone CC 19 in material examined from the Buena corehole at a depth of 1273 ft. The next lower sample (1320 ft) contained Cenomanian (Zone CC 10b) calcareous nannofossils. The intervening 50 ft was not sampled, but it is likely that a major unconformity or condensed section is present in this core. Greg Gohn (USGS, pers. commun., 1995) reports that little or no Magothy Formation (Santonian) is apparent on the gamma log.

Marshalltown Formation
Zone CC 20, Zone CC 21
early late Campanian

The Marshalltown Formation, which unconformably overlies the Englishtown Formation throughout New Jersey, is typically a massive, dark-greenish-gray, very fine glauconite sand (Owens et al., 1977). Its thickness in the subsurface varies, but it is typically less than 30 feet.

Sugarman et al. (1995) reported a middle Campanian age (Zone CC 20/21) for the Marshalltown Formation in the Clayton core between 540 and 505 ft. Bukry (in Sugarman et al., 1995) reported *Ceratolithoides aculeus*, the marker species whose FAD defines the base of Zone CC 20, at the base of the Marshalltown Formation. However, he did not record *Quadrum sissinghii*, the marker species for the base of Zone CC 21. The current authors document the occurrence of *C. aculeus* in the lower part of this formation (from 540-526 ft), along with the absence of *Q. sissinghii,* suggesting that the lower part of the Marshalltown falls within Zone CC 20. Also documented by the authors is the presence of *Q. sissinghii* in the Clayton core at 525 ft, which places the middle-upper part of the Marshalltown Formation in Zone CC 21 (middle to upper Campanian). It should be noted, however, that the genus *Quadrum* does not appear with any regularity in New Jersey and therefore cannot be considered to be a very reliable marker in this geographic area. It is possible that the upper part of the Marshalltown is actually in Zone CC 22 and that the marker species *Q. trifidum* is just not present. *Quadrum sissinghii* and *Q. trifidum* occur in great abundance in sediments of a similar age in South Carolina, suggesting that the *Quadrum* genus may be latitudinally or temperature controlled and that during the Cretaceous cooler waters off what is now New Jersey were not conducive to the propagation of this genus. The authors have also documented in South Carolina the presence of a species that is only present in Zone CC 22. This species, *Hexalithus gardetae*, was not documented in the Marshalltown, further corroborating assignment to Zone CC 21.

Mount Laurel Sand

Zone CC 22c; latest late Campanian

The Mount Laurel Sand consists of thinly bedded clays and sands that alternate with massively bedded sands and thin pebbly beds (Olsson et al., 1988). Glauconite is common in the sandy units in percentages that can reach as high as 50 percent.

Bukry (in Sugarman et al., 1995) reported that this formation contains both *Reinhardtites levis* (FAD defines the base of Perch-Nielsen's Zone CC 22c) and *Reinhardtites anthophorus* (LAD defines the top of Zone 22c). The LAD of *R. anthophorus* is considered to represent the top of the Campanian Stage and is used by calcareous nannofossil workers to represent the Campanian-Maastrichtian boundary. It should be noted, however, that this boundary is currently in dispute (Burnett et al., 1992; Sugarman et al., 1995). Placement of this boundary varies, depending on which micro- or macrofossil biostratigraphy is used. For example, the LAD of the ammonite *Nostoceras hyatti* is considered to be one of the more reliable Campanian-Maastrichtian boundary markers. It disappears slightly later than does the calcareous nannofossil *R. anthophorus*. The LAD of the planktonic foraminifera, *Globotruncanita calcarata*, which has a different range than the nannofossil and ammonite markers, is considerably below that of *R. anthophorus* (see Burnett et al., 1992; fig. 2).

Navesink Formation

Subzone CC 26a, Subzone CC 25b, Subzone CC 25a; late Maastrichtian

The Navesink Formation consists of massive, greenish-gray, poorly sorted, clayey glauconitic sands. Contact with the underlying Mount Laurel Formation is sharp, and a large unconformity between the two, spanning Zones CC 23 through CC 24, is documented using calcareous nannofossils. The Navesink is extremely fossiliferous, especially at its base, and thins in both outcrop and subsurface from the north to southwest in New Jersey (Olsson and Wise, 1987a).

Older Maastrichtian material (Subzones CC 25a and 25b) is present in New Jersey and has been documented from the Clayton and Freehold cores, as well as in outcrop (Sugarman et al., 1995). Subzone CC 25a is a partial range zone, and its base is delineated by the LAD of *Reinhardtites levis*. The base of Subzone CC 25b, and consequently the top of Subzone CC 25a, is defined by the FAD of *Lithraphidites quadratus*. Further subdivision of Zone CC 25 is based on the FAD and LAD of *Micula praemurus*, which appears in mid Subzone CC 25a and disappears in mid Subzone CC 25c, just before the appearance of *Micula murus*, the zonal marker for the base of Subzone CC 25c. Subzone CC 25c has not been reported from New Jersey.

Examination of calcareous nannofossils from the Clayton core shows the top of the Navesink Formation to be in Subzone CC 26a (Maastrichtian) based on the presence of *Nephrolithus frequens*. This species is known to be time-transgressive, first appearing in Zone CC 22 in higher latitudes and gradually appearing later in time as it moves into more subtropical regions (Huber and Watkins, 1992). The Cretaceous-Tertiary boundary in this core is at about 360 ft based on the core and gamma ray log. The youngest Cretaceous sample examined was at 373 ft, above which there is missing section up to 364 ft, where the Tertiary Hornerstown Formation is encountered. The very top of the Maastrichtian (Subzone CC 26b), the base of which is defined by the FAD of *Micula prinsii*, has not been reported from New Jersey, and this zone is thought to be missing.

BIOSTRATIGRAPHY OF PALEOGENE SEDIMENTARY UNITS

Calcareous Nannofossil Zonal Indicators

In this study, the biostratigraphic zonation of the Paleogene strata from 25 drillholes in New Jersey (fig. 1) is based primarily upon the calcareous nannofossil zonation of Martini (1971) and secondarily upon the zonation of Bukry (1973, 1975, 1978) and Okada and Bukry (1980). In the subsurface marine strata of New Jersey, calcareous nannofossil assemblages typically are sufficient in numbers of specimens, diversity of taxa, and preservational state to allow precise dating of almost all samples. Bybell and Self-Trail (1995) did a detailed study of the calcareous nannofossils across the Paleocene-Eocene boundary in New Jersey, and the nomenclature and results from that paper are used here.

Table 2 contains calcareous nannofossil species that can be used to date sediments of Paleocene, Eocene, and Oligocene age in New Jersey. The authors have found the remaining species to be biostratigraphically useful in the Gulf of Mexico and Atlantic coastal plains. FAD's and LAD's of species can be placed inside a particular calcareous nannofossil zone with a high degree of accuracy, but the relative positions of individual species within a zone are much less accurate. One exception is in Zone NP 9; here the relative placements are fairly accurate. Many of the species listed on table 2 are illustrated in Perch-Nielsen (1985b).

The following list gives the approximate length of time in millions of years for relevant NP Zones as presented in Berggren et al. (1985). Numbers in parenthesis are from Berggren et al. (in press).

Zone NP 25	4.4	(3.6)
Zone NP 24	2.2	(2.4)
Zone NP 23	4.3	(2.4)
Zone NP 22	0.5	(0.5)
Zone NP 21	1.8	(1.4)
Zone NP 19/20	0.9	(1.8)
Zone NP 18	2.1	(1.0)
Zone NP 17	2.3	(3.4)
Zone NP 16	3.1	(3.0)
Zone NP 15	4.6	(3.9)
Zone NP 14	2.6	(2.4)
Zone NP 13	1.1	(0.9)
Zone NP 12	1.5	(2.25)
Zone NP 11	1.4	(0.76)
Zone NP 10	1.2	(1.39)
Zone NP 9	1.4	(1.2)
Zone NP 8	0.8	(1.1)
Zone NP 7	0.5	(0.2)
Zone NP 6	1.2	(0.9)
Zone NP 5	0.4	(1.3)
Zone NP 4	1.7	(2.5)
Zone NP 3	1.2	(1.6)
Zone NP 2	1.0	(0.7)

Hornerstown Formation
Zones NP 2-4; early Paleocene

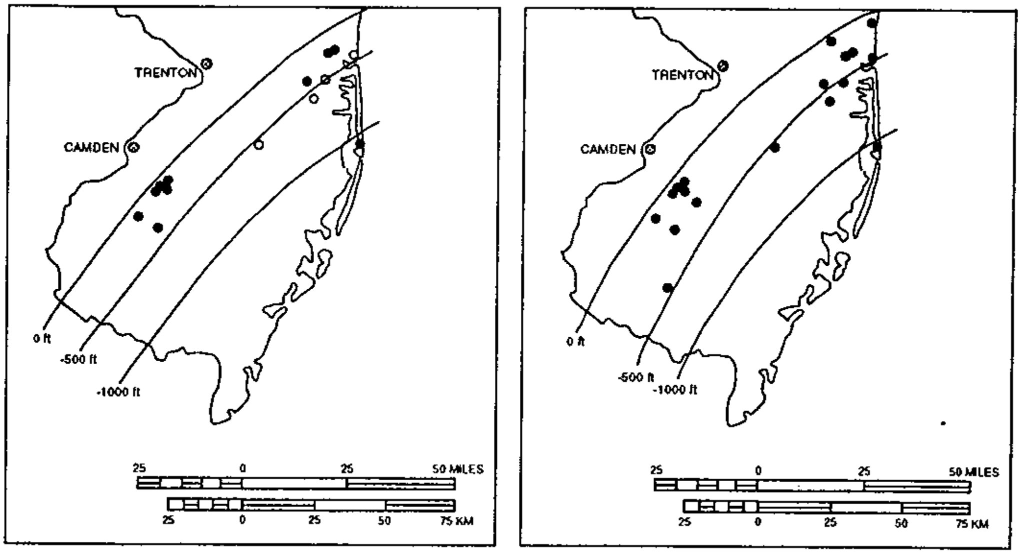
In New Jersey, the Hornerstown Formation commonly is a yellowish-green to greenish-black, clayey, massive, highly glauconitic, fine sand. This formation occurs both in surface exposures and in the subsurface of southern New Jersey. However, these occurrences are confined almost entirely to more updip locations (fig. 2). During deposition of the Hornerstown Formation, sea level was very high and the shoreline was very far inland from today's. Consequently, the thickest deposition occurred where we find most of the preserved sediments today (updip area). Downdip from this area, there was a rapid decrease in amount of sediment being deposited, and these thinner or condensed deposits could be eroded easily during subsequent times of lower sea level (Gibson et al., 1992). The Hornerstown is present as a noneroded remnant in one downdip corehole at Island Beach that was drilled during Ocean Drilling Program (ODP) Leg 150X (fig. 1). An earlier drillhole from Island Beach does not appear to contain any Hornerstown sediments. The other far downdip holes that were examined in New Jersey were not drilled deeply enough to reach the Hornerstown Formation.

The Hornerstown Formation is early Paleocene in age. Upper Cretaceous sediments of a similar but not precisely the same lithology are placed by the current authors, Gohn (this volume), and Sugarman and Owens (1994) in the Navesink Formation, and this unit is always separated from the Hornerstown by an unconformable surface. In most cases, this unconformity encompasses the uppermost Maastrichtian calcareous nannofossil Zone CC 26b and the lowermost Paleocene calcareous nannofossil Zones NP 1-2. The only Zone NP 2 sample that the authors have found in New Jersey occurs in the Allaire State Park-1 (ASP-1) hole (fig. 1). Although Zone NP 2 is missing elsewhere in New Jersey, Zones NP 3 and NP 4 are common in updip locations (fig. 2). Zone NP 3 sediments are absent in all examined downdip samples. However, the presence of *Ellipsolithus macellus* (FAD defines the base of Zone NP 4) in the Island Beach corehole from ODP Leg 150X at 1183.3 ft indicates that the upper part of the Hornerstown (NP 4) has been preserved locally in more downdip locations. Miller et al. (1993) placed overlying sediments in the same core from 1179-1167.8 ft in Zone NP 3. However, in our examination of sediments from this interval, we found *E. macellus* at 1179.9 ft (placing this sample in Zone NP 4) and *Chiasmolithus bidens* (FAD in Zone NP 5)

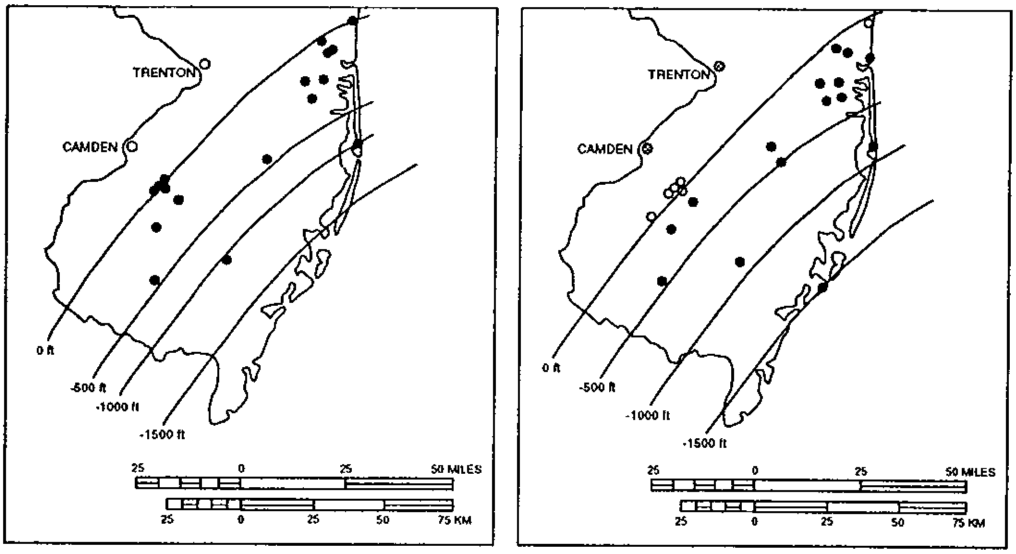
Table 2. Biostratigraphically useful Paleogene calcareous nannofossil species. For Series, e=early, e/m=early/middle, m=middle, and l=late.

LAD or FAD	**Species Name**	**Martini zonation**	**Bukry zonation**	**Series**
LAD#	*Dictyococcites bisectus*	top NP 25	**top CP 19b**	l Oligocene
LAD#	*Sphenolithus ciperoensis*	top NP 25	**top CP 19b**	l Oligocene
LAD	*Zygrhablithus bijugatus*	top NP 25	in CP 19b	l Oligocene
LAD*	*Helicosphaera recta*	**top NP 25**	in CP 19b	l Oligocene
LAD*#	*Sphenolithus distentus*	**base NP 25**	**top CP 19a**	l Oligocene
FAD	*Helicosphaera recta*	in NP 24	in CP 19a	l Oligocene
FAD*#	*Sphenolithus ciperoensis*	**base NP 24**	**base CP 19a**	l Oligocene
FAD#	*Sphenolithus distentus*	in NP 23	**base CP 18**	e Oligocene
LAD#	*Reticulofenestra hillae*	top NP 22	**top CP 16c**	e Oligocene
LAD*#	*Reticulofenestra umbilica*	**top NP 22**	**top CP 16c**	e Oligocene
LAD*#	*Cyclococcolithus formosus*	**top NP 21**	**top CP 16b**	e Oligocene
LAD	*Isthmolithus recurvus*	in NP 21	in CP 16a/b	e Oligocene
LAD	*Cyclococcolithus protoannulus*	in NP 21	in CP 16a/b	e Oligocene
LAD	*Pedinocyclus larvalis*	in NP 21	in CP 16a/b	e Oligocene
LAD	*Pemma papillatum*	in NP 21	in CP 16a/b	e Oligocene
LAD*#	*Discoaster saipanensis*	**top NP 19/20**	**top CP 15b**	l Eocene
LAD	*Cribrocentrum reticulatum*	top NP 19/20	**top CP 15b**	l Eocene
LAD#	*Discoaster barbadiensis*	top NP 19/20	**top CP 15b**	l Eocene
FAD*#	*Isthmolithus recurvus*	**base NP 19/20**	**base CP 15b**	l Eocene
FAD*#	*Chiasmolithus oamaruensis*	**base NP 18**	**base CP 15a**	m Eocene
LAD#	*Discoaster bifax*	top NP 16	**top CP 14a**	m Eocene
LAD*#	*Chiasmolithus bidens/solitus*	**top NP 16**	**top CP 14a**	m Eocene
FAD	*Cribrocentrum reticulatum*	in NP 16	in CP 14a	m Eocene
FAD	*Pemma papillatum*	in NP 16	in CP 14a	m Eocene
FAD#	*Discoaster bifax*	near base NP 16	**base CP 14a**	m Eocene
FAD#	*Reticulofenestra umbilica*	near base NP 16	**base CP 14a**	m Eocene
LAD*	*Rhabdosphaera gladius*	**top NP 15**	in CP 13c	m Eocene
LAD#	*Chiasmolithus gigas*	in NP 15	**top CP 13b**	m Eocene
FAD#	*Chiasmolithus gigas*	in NP 15	**base CP 13b**	m Eocene
FAD	*Pentaster lisbonensis*	in NP 15	in CP 13a	m Eocene
FAD*#	*Nannotetrina fulgens*	**base Np 15**	**base CP 13a**	m Eocene
LAD#	*Rhabdosphaera inflata*	in NP 14	**top CP 12b**	m Eocene
FAD	*Daktylethra punctulata*	uppermost NP 14	in CP 12b	m Eocene
FAD	*Lanternithus minutus*	uppermost NP 14	in CP 12b	m Eocene
FAD	*Pedinocyclus larvalis*	in NP 14	in CP 12b	e/m Eocene
FAD#	*Rhabdosphaera inflata*	in NP 14	**base CP 12b**	e/m Eocene
LAD	*Chiphragmalithus acanthodes*	in NP 14	in CP 12a	e/m Eocene
FAD	*Lithostromation operosum*	in NP 14	in CP 12a	e/m Eocene
FAD	*Chiasmolithus grandis*	in NP 14	in CP 12a	e/m Eocene
FAD	*Lophodolithus mochlophorus*	in NP 14	in CP 12a	e/m Eocene
FAD	*Pemma basquense*	in NP 14	in CP 12a	e/m Eocene
FAD	*Pemma rotundum*	in NP 14	in CP 12a	e/m Eocene
FAD	*Chiphragmalithus acanthodes*	in NP 14	in CP 12a	e/m Eocene
FAD*#	*Discoaster sublodoensis*	**base NP 14**	**base CP 12a**	e Eocene
FAD	*Blackites spinosus*	in NP 13	in CP 11	e Eocene
FAD	*Blackites tenuis*	in NP 13	in CP 11	e Eocene
LAD*	*Rhomboaster orthostylus*	**top NP 12**	in CP 11	e Eocene
FAD	*Helicosphaera lophota*	near top NP 12	in CP 11	e Eocene
FAD	*Reticulofenestra* spp.	near top NP 12	in CP 11	e Eocene
FAD	*Helicosphaera seminulum*	mid NP 12	in CP 11	e Eocene
FAD#	*Coccolithus crassus*	in NP 12	**base CP 11**	e Eocene
FAD	*Blackites creber*	in NP 12	in CP 10	e Eocene
LAD	*Ellipsolithus macellus*	in NP 12	in CP 10	e Eocene

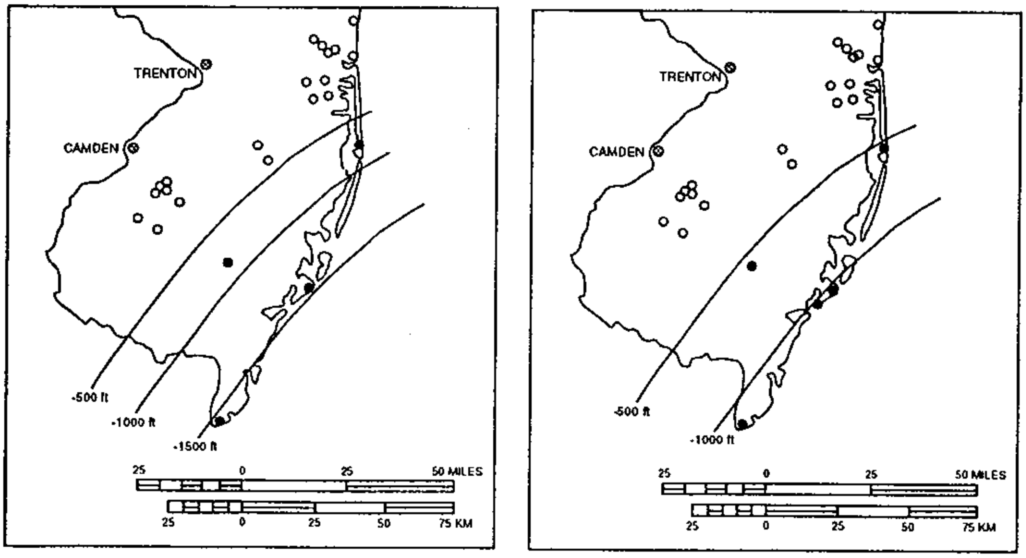
LAD or FAD	**Species Name**	**Martini zonation**	**Bukry zonation**	**Series**
FAD	*Discoaster mirus*	in NP 12	in CP 10	e Eocene
LAD	*Chiphragmalithus calathus*	in NP 12	in CP 10	e Eocene
LAD	*Rhabdosphaera truncata*	in NP 12	in CP 10	e Eocene
FAD	*Transversopontis pulcheroides*	in NP 12	in CP 10	e Eocene
FAD*#	*Discoaster lodoensis*	**base NP 12**	**base CP 10**	e Eocene
FAD	*Chiphragmalithus calathus*	near top NP 11	in CP 9b	e Eocene
FAD	*Rhabdosphaera truncata*	in NP 11	in CP 9b	e Eocene
LAD	*Discoaster multiradiatus*	in NP 11	in CP 9b	e Eocene
LAD	*Zygodiscus herlyni*	in NP 11	in CP 9b	e Eocene
FAD	*Discoaster binodosus*	in NP 11	in CP 9b	e Eocene
LAD*#	*Rhomboaster contortus*	**top NP 10**	**top CP 9a**	e Eocene
FAD	*Rhomboaster orthostylus*	upper NP 10	in CP 9a	e Eocene
FAD#	*Rhomboaster contortus*	mid NP 10	**base CP 9a**	e Eocene
FAD#	*Discoaster diastypus*	mid NP 10	**base CP 9a**	e Eocene
LAD	*Placozygus sigmoides*	lower NP 10	in CP 8b	e Eocene
LAD	*Fasciculithus* spp.	lower NP 10	in CP 8b	e Eocene
LAD	*Hornibrookina* spp.	lower NP 10	in CP 8b	e Eocene
FAD*	*Rhomboaster bramlettei*	**base NP 10**	in CP 8b	e Eocene
FAD	*Transversopontis pulcher*	upper NP 9	in CP 8b	l Paleocene
FAD	*Discoaster mediosus*	upper NP 9	in CP 8b	l Paleocene
FAD	*Toweius occultatus*	upper NP 9	in CP 8b	l Paleocene
FAD	*Discoaster mediosus*	upper NP 9	in CP 8b	l Paleocene
LAD	*Biantholithus astralis*	upper NP 9	in CP 8b	l Paleocene
FAD	*Discoaster falcatus*	upper NP 9	in CP 8b	l Paleocene
FAD	*Fasciculithus schaubii*	upper NP 9	in CP 8b	l Paleocene
FAD	*Toweius callosus*	in NP 9	in CP 8b	l Paleocene
FAD	*Lophodolithus nascens*	in NP 9	in CP 8b	l Paleocene
FAD#	*Campylosphaera dela*	in NP 9	**base CP 8b**	l Paleocene
FAD	*Discoaster lenticularis*	near base NP 9	in CP 8a	l Paleocene
FAD*#	*Discoaster multiradiatus*	**base NP 9**	**base CP 8a**	l Paleocene
FAD#	*Discoaster nobilis*	in NP 8	**base CP 7**	l Paleocene
FAD*	*Heliolithus riedelii*	**base NP 8**	in CP 6	l Paleocene
FAD#	*Discoaster mohleri*	probl. base NP 7	**base CP 6**	l Paleocene
FAD*#	*Heliolithus kleinpellii*	**base NP 6**	**base CP 5**	l Paleocene
FAD	*Heliolithus cantabriae*	upper part NP 5	in CP 4	l Paleocene
FAD	*Scapholithus apertus*	in NP 5	in CP 4	l Paleocene
FAD	*Chiasmolithus bidens*	in NP 5	in CP 4	l Paleocene
FAD	*Toweius eminens* var. *tovae*	in NP 5	in CP 4	l Paleocene
FAD*#	*Fasciculithus tympaniformis*	**base NP 5**	**base CP 4**	l Paleocene
FAD	*Chiasmolithus* aff. *C. bidens*	in NP 4	in CP 3	e Paleocene
FAD	*Toweius eminens*	in NP 4	in CP 3	e Paleocene
FAD	*Toweius pertusus*	in NP 4	in CP 3	e Paleocene
FAD	*Ellipsolithus distichus*	near base NP 4	in CP 3	e Paleocene
FAD*#	*Ellipsolithus macellus*	**base NP 4**	**base CP 3**	e Paleocene
FAD	*Chiasmolithus consuetus*	in NP 3	in CP 2	e Paleocene
FAD*#	*Chiasmolithus danicus*	**base NP 3**	**base CP 2**	e Paleocene
FAD*#	*Cruciplacolithus tenuis*	**base NP 2**	**base CP 1b**	e Paleocene
LAD*	*Arkhangelskiella cymbiformis*	**top Cretaceous**	**top Cretaceous**	l Cretaceous
LAD#	*Micula mura*	**top Cretaceous**	**top Cretaceous**	l Cretaceous


HORNERSTOWN FORMATION NP 2-4

VINCENTOWN FORMATION NP 5-9


MANASQUAN FORMATION NP 9-14

SHARK RIVER FORMATION NP 14-18


ACGS ALPHA UNIT NP 18-21

ACGS BETA UNIT NP 24-25

Figure 2. Subsurface distribution of Paleogene units in New Jersey. Solid circles represent drillholes that contain sediments for each unit, and open circles indicate drillholes in which these sediments are presumed to have been removed by erosion. Contour lines indicate number of feet below sea level for the base of each unit.

at 1168.2 ft (placing this sample in Zone NP 5).

In the mid-Atlantic coastal plain, the formation that is the closest in age to the Hornerstown is the Brightseat Formation of Maryland, which is placed in Zone NP 3 (Bybell and Gibson, 1994; Gibson and Bybell, 1994) and a unit in Delaware, which tentatively has been called Brightseat and is placed in Zone NP 4 (Bybell et al.,1995).

Vincentown Formation
Zones NP 5-9; late Paleocene

The Vincentown Formation in New Jersey commonly is a green-to-brown, glauconitic quartz sand. These sediments occur in surface exposures only in updip portions of southern New Jersey, but they are more widespread in the subsurface (fig. 2). The Vincentown is not necessarily absent in more downdip wells; these sediments were not reached during drilling.

Strata placed in Zones NP 5, 8, and 9 have the most widespread distribution in New Jersey. Zones NP 6-7 are much more limited in their geographic extent. Zone NP 6 is confined to the northern part of the study area (the region north of Camden, fig. 2), and Zone NP 7 is confined to the southern part of the study area (Bybell, 1992). This difference probably indicates some instability during this period of time that could be the result of tectonics, shifting sediments sources, etc. Erosion alone cannot adequately explain this distribution because sediments from Zone NP 6, which are absent south of the Butler Place drillhole, can be 65 ft thick (B-5 drillhole) in the northern part of the study area.

The Vincentown Formation, which is late Paleocene in age, is equivalent in age to the Aquia Formation of Maryland and Virginia (Zones NP 5-9, Bybell and Gibson, 1994; Gibson and Bybell, 1994; Gibson and Bybell, 1995). Sediments from Delaware, which tentatively have been placed in the Aquia Formation, are in Zones NP 6, 8, and 9 (Bybell et al., 1995).

Manasquan Formation
Zones NP 9-14
latest Paleocene to early Eocene

The Manasquan Formation in New Jersey commonly is a yellow-green to olive-green, massive, calcareous clay to silt to very fine sand with extensive burrowing. This formation occurs in surface exposures east and southeast of Trenton and along the Manasquan River (Owens et al., 1988). Similar to the Vincentown Formation, the Manasquan is widespread in the subsurface of southern New Jersey (fig. 2). There are few documented occurrences of this formation in the more downdip portions of New Jersey because these sediments were not reached during drilling.

The Manasquan Formation, which contains a continuous Paleocene-Eocene boundary section in the Clayton corehole (Gibson et al., 1993), is represented by sediments of very latest Paleocene and early Eocene age (Zones NP 9-14). It is possible that the early-middle Eocene boundary (within Zone NP 14) corresponds to the boundary between the Manasquan and Shark River Formations. There is significant variation in the geographic distribution of the various calcareous nannofossil zones within the Manasquan Formation. None of these zones are represented by thick lithologic sections, and it is assumed that small variations in the amount of erosion from place to place could account for most of the distributional differences. However, Zone NP 11 and younger sediments of the Manasquan have been eroded from most updip locations. This process increases upward through Eocene and Oligocene deposits, and the higher in the Tertiary, the farther downdip the sediments are stripped away. For example, by the upper Oligocene, sediments are only preserved in the farthest downdip locations. Contour lines on figure 2 indicate feet below present sea level for the base of each of the formations. Across a 40 mile dip transect across New Jersey, the formations currently drop 1,500 ft vertically. There appears to be a significant increase in the amount of dip that occurred after deposition of these sediments. This increase appears to be tied to reactivation of uplift within the Appalachians, which resulted in greater uplift of more landward (updip) locations in the present New Jersey coastal plain. It is likely that this reactivation began during the middle Oligocene. See the discussion of the ACGS Beta unit below.

The Marlboro Clay (uppermost Zone NP 9) and Nanjemoy Formation (Zones NP 10-13) of Maryland and Virginia are the closest age equivalents to the Manasquan Formation (Bybell and Gibson, 1994; Gibson and Bybell, 1994; Gibson and Bybell, 1995). Sediments in Delaware tentatively have been placed in the Nanjemoy Formation (Zones NP 10-14, according to Bybell et al., 1995).

Shark River Formation
Zones NP 14-18
middle Eocene to early late Eocene

The Shark River Formation in New Jersey

commonly is an olive-green, massive, glauconitic, calcareous clay to silt to very fine sand with extensive burrowing. The Shark River Formation occurs as scattered outcrops along the Shark River near Asbury Park, New Jersey (Owens et al., 1988; Sugarman and Owens, 1994). This formation has wide distribution in the subsurface of southern New Jersey (fig. 2).

The Shark River is represented by middle Eocene sediments (Zones NP 14-17) and lower upper Eocene sediments (Zone NP 18). The Shark River has been completely eroded from the most updip locations in New Jersey but is well represented downdip (fig. 2). Deposits from Zones NP 15-16 are the most geographically widespread for this unit. This is reasonable because Zone NP 15 and NP 16 encompass more time than any of the other Paleocene or Eocene zones. (4.6 and 3.1 m.y., respectively, according to Berggren et al., 1985).

The Piney Point Formation (Zones NP 15-17) of Maryland and Virginia is the closest age equivalent to the Shark River Formation (Bybell and Gibson, 1994; Gibson and Bybell, 1994). In Delaware, sediments that tentatively are placed in the Piney Point Formation are in Zone NP 16 (Bybell et al., 1995).

ACGS Alpha unit

Zones NP 18-21

late Eocene-lowermost early Oligocene

This unit, which is found only in the subsurface of southern New Jersey, was first described by Owens et al. (1988). This unit is a dark-colored, locally laminated, fossiliferous, glauconitic, calcareous clay to silt to very fine sand. The ACGS Alpha unit has been eroded from much of New Jersey and has been found only in downdip drillhole material at Island Beach, Atlantic City, Cape May, and from the ACGS-4 corehole (fig. 1).

The ACGS Alpha unit is represented by upper Eocene sediments (Zones NP 18 to lower NP 21) and lower lower Oligocene sediments (upper Zone NP 21). The Chickahominy Formation of Virginia (upper Eocene) is the closest age equivalent to the ACGS Alpha unit (Owens et al., 1988). There appear to be no age-equivalent sediments in Delaware.

Mays Landing Unit

upper Zone NP 21 and possible NP 22

early Oligocene

This unit, which is found only in the subsurface of New Jersey, was first described by Owens et al. (1988). The Mays Landing unit is a greenish-gray, locally laminated, micaceous, calcareous, fossiliferous, clay to silt to sand (Owens et al., 1988). This unit, which apparently has been eroded from most of New Jersey, has been found only in the downdip ACGS-4 corehole. It is unclear at this time whether this unit is clearly a separate formation or whether it should be placed within the ACGS Alpha unit. Miller et al. (1993) did not recognize this unit in the Island Beach or Atlantic City cores.

ACGS Beta unit

Zones NP 24-25, late Oligocene

The ACGS Beta unit, which is only found in the subsurface of New Jersey, was first described by Owens et al. (1988). This unit is a grayish-green, slightly clayey, poorly sorted, slightly glauconitic, fine to medium sand. The ACGS Beta unit, which is presumed to have been eroded from most of New Jersey, has been found only in downdip drillholes at Island Beach (both drillholes), Atlantic City, Cape May, and from the ACGS-4 corehole (figs. 1, 2). This unit is unconformably overlain by the Miocene Kirkwood Formation, which is found throughout the subsurface of southern New Jersey. Both the ACGS Beta unit and the Kirkwood Formation are coarser grained than the underlying units and were deposited in shallower water (Gibson, 1983; Owens et al., 1988). A worldwide low sea-level stand existed during the middle Oligocene, and some of the erosion of the underlying deposits is believed to have occurred during this time. It is postulated that reactivation of uplift in the Appalachians may have begun at the same time. The resulting uplift of more updip locations could explain the more significant amount of erosion in these locations. However, the fact that the upper Oligocene ACGS Beta unit is thin and is found only in downdip locations indicates that this unit was deposited before large floods of detritus were carried into the area. The fact that this unit is coarser and of different clay mineral composition than underlying units (Owens et al., 1988) argues for deposition in shallower water and (or) after reactivation of the Appalachians. The updip ACGS Beta unit was then eroded prior to deposition of the widespread Kirkwood Formation, which does have a strong detrital influence.

The ACGS Beta unit is composed of upper Oligocene sediments (Zones NP 24-25). The Old Church Formation of Virginia (late Oligocene in age) is the closest age equivalent to the ACGS Beta unit (Owens et al., 1988). There are no age-equivalent sediments the Dover Je32-04 core in Delaware

(Bybell et al., 1995).

CONCLUSIONS

Cretaceous and Paleogene marine sediments in the subsurface of New Jersey were analyzed for calcareous nannofossil content and biostratigraphy. Age determination of lithostratigraphic units was possible based on calcareous nannofossil biostratigraphy. Cretaceous nannofossil distribution in New Jersey was found to be similar to distributions found elsewhere in coeval sediments in the Atlantic coastal plain. However, the absence of low-latitude species, such as *Quadrum trifidum* and *Quadrum sissinghii*, indicates that there was a latitudinal temperature difference between New Jersey and South Carolina during the Campanian and Maastrichtian. Cretaceous unconformities that have been documented in South Carolina can be extended into New Jersey, and this argues for large-scale, regional sea-level fluctuations at this time. The distribution and thicknesses of the Paleogene subsurface marine sediments and their relationship to tectonic and erosional forces suggests large-scale erosion of Eocene and Oligocene updip material with increased preservation of sections to the south and east. Reactivation of uplift of the Appalachian mountains during the middle Oligocene is postulated based on the coarsening of sediment influx during this time and on the change in dip magnitudes from updip to downdip areas of the New Jersey coastal plain.

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Appendix 1. Cretaceous Calcareous Nannofossil Species Listed in Paper

Arkhangelskiella cymbiformis Vekshina, 1959
Aspidolithus parcus constrictus (Hattner, Wind, & Wise, 1980) Perch-Nielsen, 1984
Aspidolithus parcus parcus (Stradner, 1963) Noël, 1969
Axopodorhabdus albianus (Black, 1967) Wind & Wise *in* Wise and Wind, 1977
Bukryaster hayi (Bukry, 1969) Prins & Sissingh *in* Sissingh, 1977
Calculites obscurus (Deflandre, 1959) Prins & Sissingh *in* Sissingh, 1977
Calculites ovalis (Stradner, 1963) Prins & Sissingh *in* Sissingh, 1977
Ceratolithoides aculeus (Stradner, 1961) Prins & Sissingh *in* Sissingh, 1977
Ceratolithoides kamptneri Bramlette & Martini, 1964
Ceratolithoides verbeekii Perch-Nielsen, 1979
Corollithion achylosum (Stover, 1966) Hill, 1976
Corollithion exiguum Stradner, 1961
Eiffellithus eximius (Stover, 1966) Perch-Nielsen, 1968
Eiffellithus turriseiffeli (Deflandre *in* Deflandre and Fert, 1954) Reinhardt, 1965
Eprolithus floralis (Stradner, 1962) Stover 1966
Hexalithus gardetae Bukry, 1969
Lithastrinus grillii Stradner, 1962
Lithastrinus septenarius Forchheimer, 1972
Lithraphidites acutus Verbeek & Manivit *in* Manivit et al., 1977
Lithraphidites grossopectinatus Bukry, 1969
Lithraphidites quadratus Bramlette & Martini, 1964
Lucianorhabdus cayeuxii Deflandre, 1959
Lucianorhabdus maleformis Reinhardt, 1966
Marthasterites furcatus (Deflandre *in* Deflandre and Fert, 1954) Deflandre, 1959
Microrhabdulus belgicus Hay & Towe, 1963
Microrhabdulus decoratus Deflandre, 1959
Microstaurus chiastius (Worsley, 1971) Grün *in* Grün and Allemann, 1975
Micula concava (Stradner *in* Martini and Stradner, 1960) Verbeek, 1976
Micula decussata Vekshina, 1959
Micula murus (Martini, 1961) Bukry, 1973h
Micula praemurus (Bukry, 1973h) Stradner & Steinmetz, 1984
Micula prinsii Perch-Nielsen, 1979
Nephrolithus frequens Gorka, 1957
Prediscosphaera arkhangelskyi (Reinhardt, 1965) Perch-Nielsen, 1984
Quadrum gartneri Prins & Perch-Nielsen *in* Manivit et al., 1977
Quadrum sissinghii Perch-Nielsen, 1986
Quadrum trifidum (Stradner *in* Stradner and Papp, 1961) Prins & Perch-Nielsen *in* Manivit et al., 1977
Reinhardtites anthophorus (Deflandre, 1959) Perch-Nielsen, 1968
Reinhardtites levis Prins & Sissingh *in* Sissingh, 1977
Tranolithus phacelosus Stover, 1966
Watznaueria barnesae (Black *in* Black and Barnes, 1959) Perch-Nielsen, 1968

Appendix 2. Cenozoic Calcareous Nannofossil Species Listed in Paper

Biantholithus astralis Steinmetz & Stradner, 1984
Blackites creber (Deflandre *in* Deflandre and Fert, 1954) Stradner & Edwards
Blackites spinosus (Deflandre & Fert, 1954) Hay & Towe, 1962
Blackites tenuis (Bramlette & Sullivan, 1961) Sherwood, 1974
Blackites truncatus (Bramlette & Sullivan, 1961) Varol, 1989
Campylosphaera dela (Bramlette & Sullivan, 1961) Hay & Mohler, 1967
Chiasmolithus bidens (Bramlette & Sullivan, 1961) Hay & Mohler, 1967
Chiasmolithus consuetus (Bramlette & Sullivan, 1961) Hay & Mohler, 1967
Chiasmolithus danicus (Brotzen, 1959) Hay & Mohler, 1967
Chiasmolithus gigas (Bramlette & Sullivan, 1961) Hay,

Mohler, & Wade, 1966

Chiasmolithus grandis (Bramlette & Riedel, 1954) Hay, Mohler, & Wade, 1966

Chiasmolithus oamaruensis (Deflandre *in* Deflandre and Fert, 1954) Hay, Mohler, & Wade, 1966

Chiasmolithus solitus (Bramlette & Sullivan, 1961) Hay, Mohler, & Wade, 1966

Chiphragmalithus acanthodes Bramlette & Sullivan, 1961

Chiphragmalithus calathus Bramlette & Sullivan, 1961

Coccolithus crassus Bramlette & Sullivan, 1961

Cribrocentrum reticulatum (Gartner & Smith, 1967) Perch-Nielsen, 1971

Cruciplacolithus tenuis (Stradner, 1961) Hay & Mohler *in* Hay et al., 1967

Cyclococcolithus formosus Kamptner, 1963

Cyclococcolithus protoannulus (Gartner, 1971) Haq & Lohmann, 1976

Daktylethra punctulata Gartner *in* Gartner and Bukry, 1969

Dictyococcites bisectus (Hay, Mohler, & Wade, 1966) Bukry & Percival, 1971

Discoaster barbadiensis Tan Sin Hok, 1927

Discoaster bifax Bukry, 1971

Discoaster binodosus Martini, 1958

Discoaster diastypus Bramlette & Sullivan, 1961

Discoaster falcatus Bramlette & Sullivan, 1961

Discoaster lenticularis Bramlette & Sullivan, 1961

Discoaster lodoensis Bramlette & Riedel, 1954

Discoaster mediosus Bramlette & Sullivan, 1961

Discoaster minus Deflandre *in* Deflandre and Fert, 1954

Discoaster mohleri Bukry & Percival, 1971

Discoaster multiradiatus Bramlette & Riedel, 1954

Discoaster nobilis Martini, 1961

Discoaster saipanensis Bramlette & Riedel, 1954

Discoaster sublodoensis Bramlette & Sullivan, 1961

Ellipsolithus distichus (Bramlette & Sullivan, 1961) Sullivan, 1964

Ellipsolithus macellus (Bramlette & Sullivan, 1961) Sullivan, 1964

Emiliania huxleyi (Lohmann, 1902) Hay & Mohler *in* Hay et al., 1967

Fasciculithus schaubii Hay & Mohler, 1967

Fasciculithus tympaniformis Hay & Mohler *in* Hay et al., 1967

Helicosphaera compacta Bramlette & Wilcoxon, 1967

Helicosphaera lophota (Bramlette & Sullivan, 1961) Locker, 1973

Helicosphaera recta Jafar & Martini, 1975

Helicosphaera seminulum Bramlette & Sullivan, 1961

Heliolithus cantabriae Perch-Nielsen, 1971

Heliolithus kleinpellii Sullivan, 1964

Heliolithus riedelii Bramlette & Sullivan, 1961

Isthmolithus recurvus Deflandre *in* Deflandre and Fert, 1954

Lanternithus minutus Stradner, 1962

Lithostromation operosum (Deflandre *in* Deflandre and Fert, 1954) Bybell, 1975

Lophodolithus mochlophorus Deflandre *in* Deflandre and Fert, 1954

Lophodolithus nascens Bramlette & Sullivan, 1961

Markalius inversus (Deflandre *in* Deflandre and Fert, 1954) Bramlette & Martini, 1964

Nannotetrina fulgens (Stradner, 1960) Achuthan & Stradner, 1969

Pedinocyclus larvalis Bukry & Bramlette, 1971

Pemma basquense (Martini, 1959) Bybell & Gartner, 1972

Pemma papillatum Martini, 1959

Pemma rotundum Klumpp, 1953

Pentaster lisbonensis Bybell & Gartner, 1972

Placozygus sigmoides (Bramlette & Sullivan, 1961) Romein, 1979b

Reticulofenestra hillae Bukry & Percival, 1971

Reticulofenestra umbilica (Levin, 1965) Martini & Ritzkowski, 1968

Rhabdosphaera gladius Locker, 1967

Rhabdosphaera inflata Bramlette & Sullivan, 1961

Rhabdosphaera truncata Bramlette & Sullivan, 1961

Rhomboaster bramlettei (Brönnimann & Stradner, 1960) Bybell & Self-Trail, 1995

Rhomboaster contortus (Stradner, 1958) Bybell & Self-Trail, 1995

Rhomboaster orthostylus (Shamrai, 1963) Bybell & Self-Trail, 1995

Scapholithus apertus Hay & Mohler, 1967

Sphenolithus ciperoensis Bramlette & Wilcoxon, 1967

Sphenolithus distentus (Martini, 1965) Bramlette & Wilcoxon, 1967

Toweius callosus Perch-Nielsen, 1971b

Toweius eminens (Bramlette & Sullivan, 1961) Gartner, 1971a

Toweius eminens var. *tovae* Bybell & Self-Trail, 1995

Toweius occultatus (Locker, 1967) Perch-Nielsen, 1971

Toweius pertusus (Sullivan, 1965) Romein, 1979b

Transversopontis pulcher (Deflandre *in* Deflandre and Fert, 1954) Perch-Nielsen, 1967

Transversopontis pulcheroides (Sullivan, 1964) Baldi-Beke, 1971

Zygodiscus herlyni Sullivan, 1964

Zygrhablithus bijugatus (Deflandre *in* Deflandre and Fert, 1954) Deflandre, 1959

PLATE I

[SEM, scanning electron micrograph; XP, cross-polarized light]

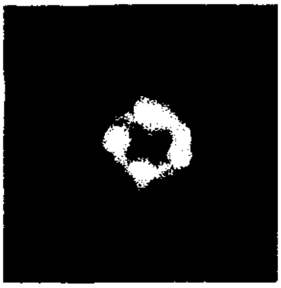
Figures 1,4. ***Eprolithus floralis***
1. XP (length, 6.8 µm), Subzone CC 10b, Buena core (1350 ft), New Jersey.
4. XP (length, 6.8 µm), Subzone CC 10b, Buena core (1350 ft), New Jersey.

2. ***Microrhabdulus decoratus***
XP (length, 16.1µm), Subzone CC 18c, Clayton core (656.4 ft), New Jersey.

3, 5, 8. ***Eiffellithus turriseiffelii***
3. SEM, distal view (length, 8.7 µm), Subzone CC 18c, Clayton core (649 ft), New Jersey.
5. XP (length, 8.9 µm), Subzone CC 26a, Clayton core (380.2 ft), New Jersey.
8. SEM, distal view (length, 5.9 µm), Subzone CC 18a, Clayton core (659.0 ft), New Jersey.

7. ***Eiffellithus eximius***
XP (length, 7.6 µm), Subzone CC 18c, Clayton core (656.4 ft), New Jersey.

6, 9-11. ***Micula decussata***
6. XP (length, 7.8 µm), Subzone CC 22c, St. George core (816.0 ft), South Carolina.
9. XP (length, 9.4 µm), Subzone CC 26a, Clayton core (380.2 ft), New Jersey.
10. SEM (diameter, 8.1 µm), Subzone CC 18a, Clayton core (659.0 ft), New Jersey.
11. SEM (diameter, 8.3 µm), Subzone CC 18c, Clayton core (649.0 ft), New Jersey.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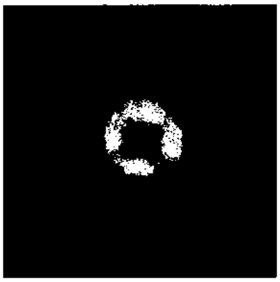
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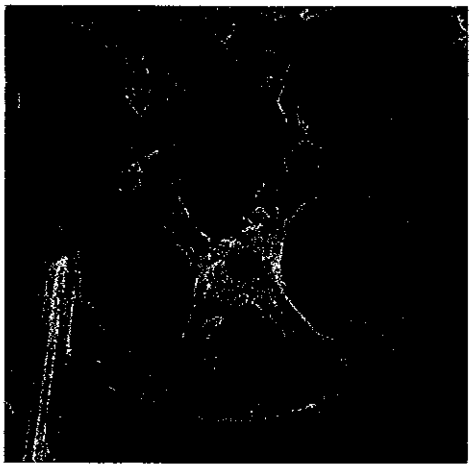
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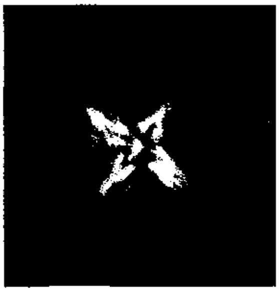
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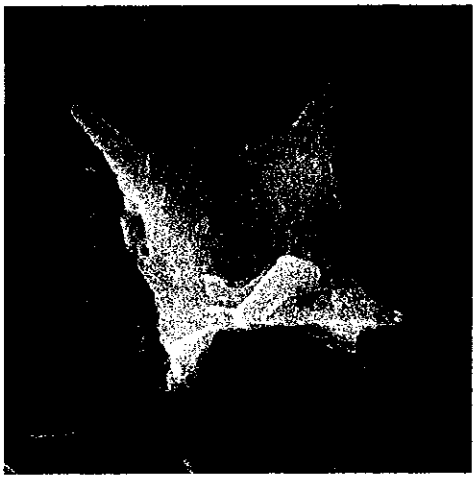
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PLATE II

[SEM, scanning electron micrograph; XP, cross-polarized light]

Figuresl, 4. *Lithastrinus grillii*

1. XP (length, 4.7 µm), Subzone CC 18c, Clayton core (656.4 ft), New Jersey.
4. XP (length, 8.3 µm), Subzone CC 18c, Clayton core (656.4 ft), New Jersey.

2, 3, 5. *Lucianorhabdus cayeuxii*

2. XP (length, 9.4 µm), Subzone CC 18c, Clayton core (656.4 ft), New Jersey.
3. SEM, side view (length, 14.7 µm), Subzone CC 18c, Clayton core (649.0 ft), New Jersey.
5. XP (length, 15.1 µm), Subzone CC 18c, Clayton core (656.4 ft), New Jersey.

6. *Calculites obscurus*

XP (length, 5.2 µm), Subzone CC 18c, Clayton core (656.5 ft), New Jersey.

7. *Aspidolithus parcus parcus*

XP (length, 11.5 µm), Subzone CC 22b, Lake City core (228 ft), South Carolina.

8-10. *Aspidolithus parcus constrictus*

8. SEM, distal view (length, 10.5 µm), Subzone CC 22c, Lake City core (178 ft), South Carolina.
9. XP (length, 10.0 µm), Subzone CC 22b, Lake City core (228 ft), South Carolina.
10. SEM, distal view (length, 10.5 µm), Subzone CC 18a, Clayton core (659.0 ft), New Jersey.

11. *Marthasterites furcatus*

SEM (width, 8.9 µm), Subzone CC 18a, Clayton core (659.0 ft), New Jersey.

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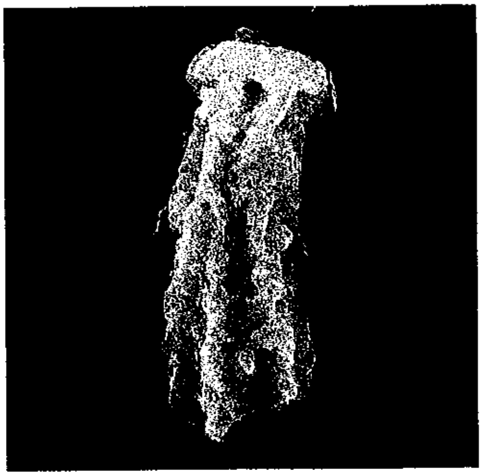

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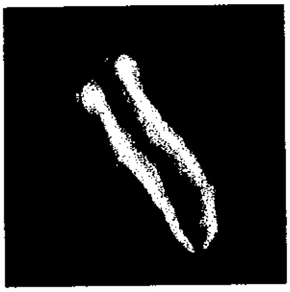

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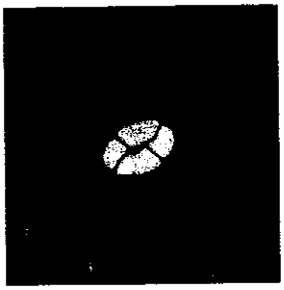

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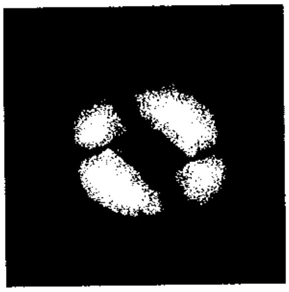

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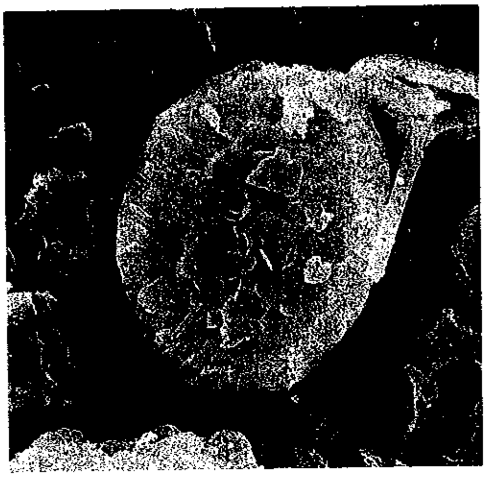

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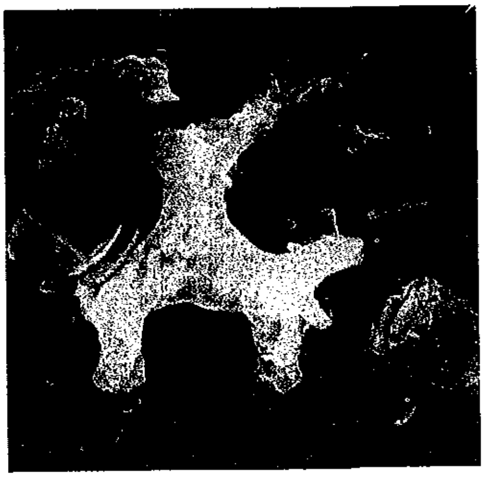

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PLATE III

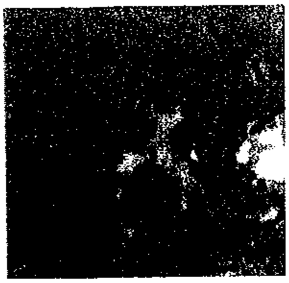
[SEM, scanning electron micrograph; XP, cross-polarized light;
TL, transmitted light]

Figures 1, 2. *Marthasterites furcatus*
1. TL (length, 9.9 μm), Subzone CC 18c, Clayton core (656.4 ft), New Jersey.
2. SEM (width, 5.6 μm), Subzone CC 18a, Clayton core (659.0 ft), New Jersey.

3-6. *Ceratolithoides aculeus*
3. SEM, side view (length, 6.6 μm), Subzone CC 22c, Lake City core (178 ft), South Carolina.
4. XP (length, 5.2 μm), Subzone CC 22c, St. George core (815 ft), South Carolina.
5. XP (length, 6.3 μm), Subzone CC 22b, Lake City core (228 ft), South Carolina.
6. SEM, side view (length, 5.0 μm), Subzone CC 22c, Lake City core (178 ft), South Carolina.

7, 8. *Quadrum sissinghi*
7. XP (length, 7.3 μm), Subzone CC 22b, Lake City core (228 ft), South Carolina.
8. XP (length, 8.6 μm), Subzone CC 22b, Lake City core (228 ft), South Carolina.

9-11. *Reinhardtites anthophorus*
9. XP (length, 7.8 μm), Subzone CC 18c, Clayton core (656.4 ft), New Jersey.
10. XP (length, 8.1 μm), Subzone CC 18c, Clayton core (656.4 ft), New Jersey.
11. SEM, distal view (length, 7.9 μm), Subzone CC 18a, Clayton core (659.0 ft), New Jersey.



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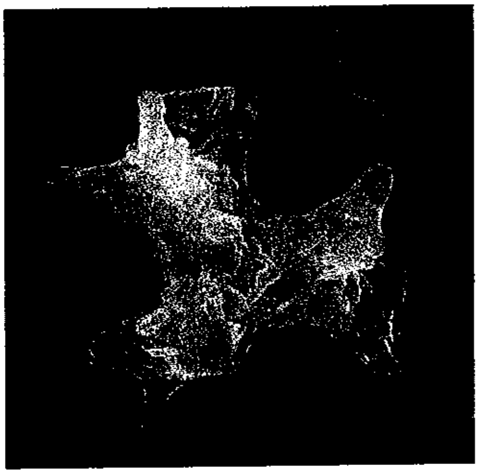

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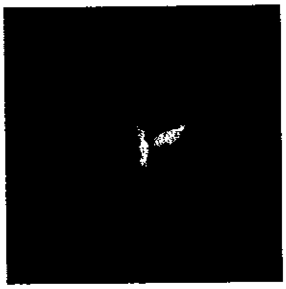

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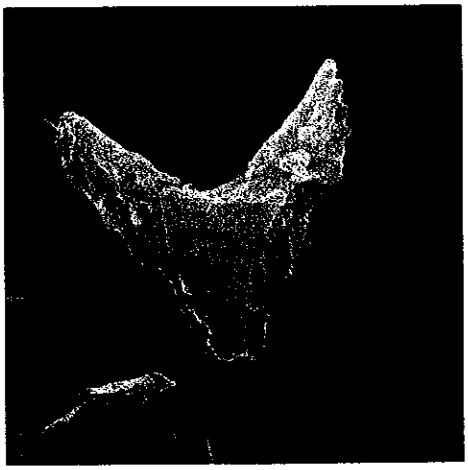

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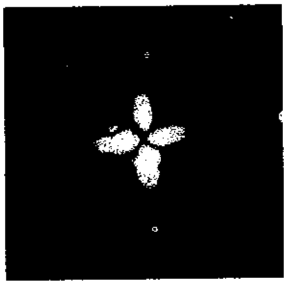

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PLATE IV

[SEM, scanning electron micrograph; XP, cross-polarized light;
TL, transmitted light]

Figures 1, 2. ***Arkhangelskiella cymbiformis***
- 1. XP (length, 9.9 µm), Subzone CC 26a, Clayton core (380.2 ft), New Jersey.
- 2. SEM, distal view (length, 8.5 µm), Subzone CC 18c, Clayton core (649.0 ft), New Jersey.

3, 5, 7, 8. ***Nephrolithus frequens***
- 3. SEM, distal view (length, 7.2 µm), Subzone CC 26a, Clayton core (380.2 ft), New Jersey.
- 5. XP (length, 8.3 µm), Subzone CC 26a, Clayton core (380.2 ft), New Jersey.
- 7. SEM, distal view (length, 6.7 µm), Subzone CC 26a, Clayton core (380.2 ft), New Jersey.
- 8. TL (length, 8.3 µm), Subzone CC 26a, Clayton core (380.2 ft), New Jersey.

4, 6. ***Lithraphidites quadratus***
- 4. XP (length, 7.8 µm), Subzone CC 26a, Clayton core (380.2 ft), New Jersey.
- 6. SEM, side view (length, 7.3 µm), Subzone CC 26a, Clayton core (380.2 ft), New Jersey.

9-11. ***Watznaueria barnesae***
- 9. XP (length, 6.3 µm), Subzone CC 26a, Clayton core (380.2 ft), New Jersey.
- 10. SEM, distal view (length, 8.3 µm), Subzone CC 18a, Clayton core (659.0 ft), New Jersey.
- 11. SEM, distal view (length, 8.5 µm), Subzone CC 18a, Clayton core (659.0 ft), New Jersey.


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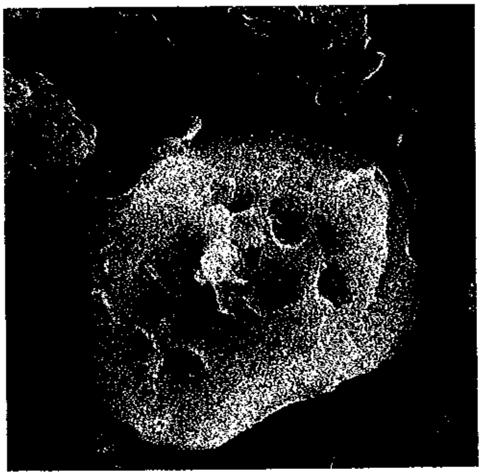
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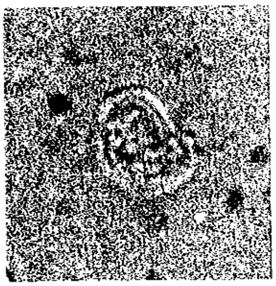
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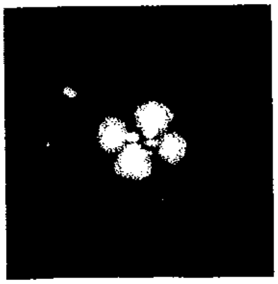
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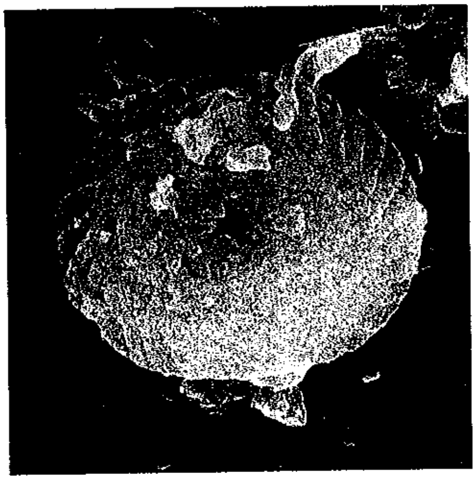
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PLATE V

[SEM, scanning electron micrograph; XP, cross-polarized light]

Figures 1,2. ***Chiasmolithus consuetus*** s.l.
  1. SEM, distal view (length, 7.1 µm), Zone NP 8, GL 915 core (135 ft), New Jersey.
  2. XP (length, 12.0 µm), Zone NP 9, Clayton core (348.5 ft), New Jersey.

3-5, 8. ***Ellipsolithus macellus***
  3. SEM, distal view (length, 12.0 µm), Zone NP 11, Butler Place core (570 ft), New Jersey.
  4. SEM, proximal view (length, 10.1 µm), Zone NP 10, Island Beach 150X core (1023.8 ft), New Jersey.
  5. XP (length, 14.6 µm), Zone NP 9, GL 915 core (130 ft), New Jersey.
  8. XP (length, 13.3 µm), Zone NP 9, GL 915 core (130 ft), New Jersey.

6,7. ***Ellipsolithus distichus***
  6. SEM, distal view (length, 11.0 µm), Zone NP 8, GL 916 core (100 ft), New Jersey.
  7. SEM, proximal view (length, 11.3 µm), Zone NP 10, GL 917 core (195 ft), New Jersey.

9. ***Chiasmolithus bidens***
  SEM, distal view (length, 9.2 µm), Zone NP 13, Silverton Road core (373.7 ft), New Jersey.

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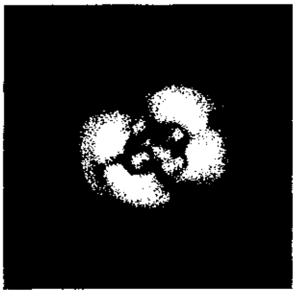

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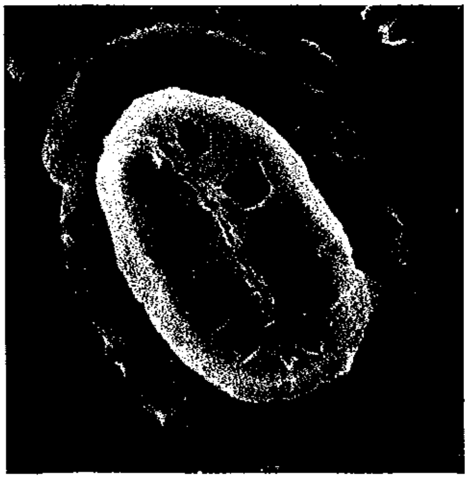

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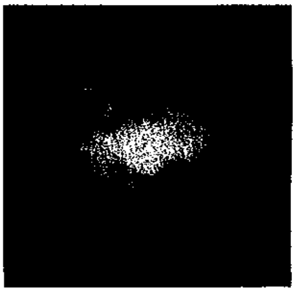

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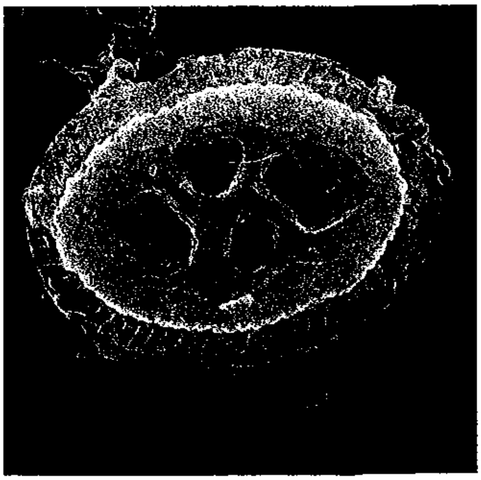

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PLATE VI

[SEM, scanning electron micrograph; XP, cross-polarized light; PC, phase contrast]

Figures 1,2. ***Chiasmolithus bidens***

1. SEM, proximal view (length, 7.3 μm), Zone NP 13, Silverton Road core (373.7 ft), New Jersey.
2. XP (length, 7.6 μm), Zone NP 9, Clayton core (321.4 ft), New Jersey.

3. ***Heliolithus cantabriae***

SEM, top oblique view (diameter, 12.3 μm), Zone NP 6, Butler Place core (630 ft), New Jersey.

4. ***Heliolithus riedelii***

SEM, side view (diameter, 9.5μm; height, 7.2μm), Zone NP 8, GL 916 core (100 ft), New Jersey.

5. ***Discoaster mohleri***

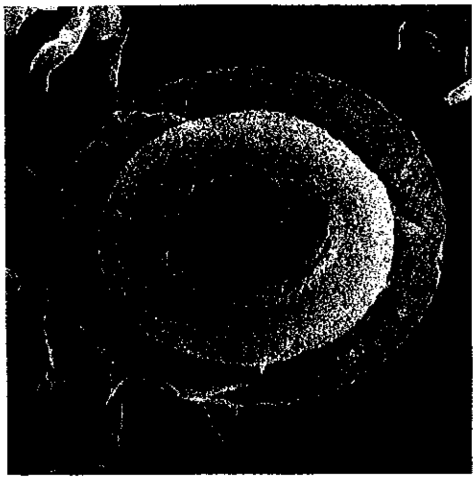
SEM, (diameter, 10.7 μm), Zone NP 7, GL 916 core (120 ft), New Jersey.

6,7. ***Discoaster multiradiatus***

6. SEM, (diameter, 8.5 μm), Zone NP 9, GL 915 core (110 ft), New Jersey.
7. PC (length, 16.4 μm), Zone NP 10, Clayton core (296.5 ft), New Jersey.

8. ***Discoaster lenticularis***

SEM, (diameter, 7.0 μm), Zone NP 9, Clayton core (306.9 ft), New Jersey.



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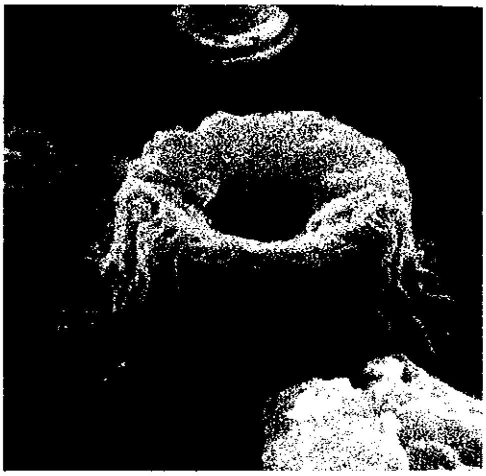

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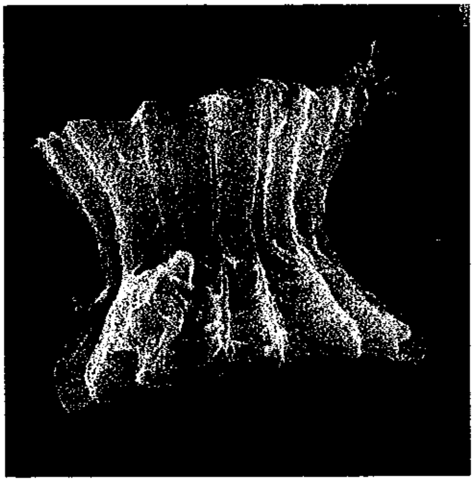

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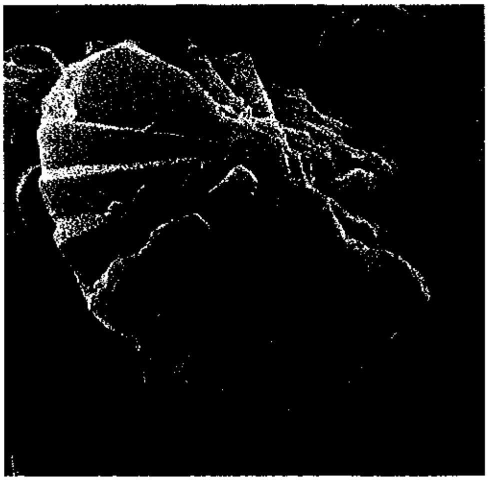

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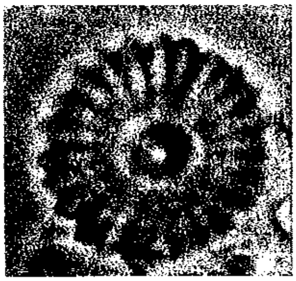

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PLATE VII

[SEM, scanning electron micrograph; XP, cross-polarized light]

Figures 1-3. *Campylosphaera dela*

1. SEM, distal view (length, 7.3 µm), Zone NP 13, Allaire State Park-2 (ASP-2) core (234.3 ft), New Jersey.
2. SEM, proximal view (length, 8.3 µm), Zone NP 14, ACGS-4 core (900 ft), New Jersey.
3. XP (length, 6.8 µm), Zone NP 9, Clayton core (314 ft), New Jersey.

4-6. *Lophodolithus nascens*

4. SEM, distal view (length, 11.7 µm), Zone NP 13, ASP-2 core (234.3 ft), New Jersey.
5. XP (length, 14.8 µm), Zone NP 9, Clayton core (314 ft), New Jersey.
6. XP (length, 9.4 µm), Zone NP 9, Clayton core (322 ft), New Jersey.

7-9. *Transversopontis pulcher*

7. SEM, distal view (length, 11.7 µm), Zone NP 14, ACGS-4 core (900 ft), New Jersey.
8. XP (length, 8.1 µm), Zone NP 9, Clayton core (317.4 ft), New Jersey.
9. XP (length, 7.3 µm), Zone NP 9, Clayton core (317.4 ft) New Jersey

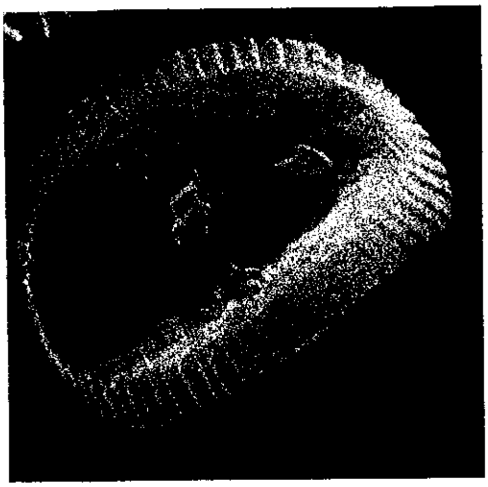

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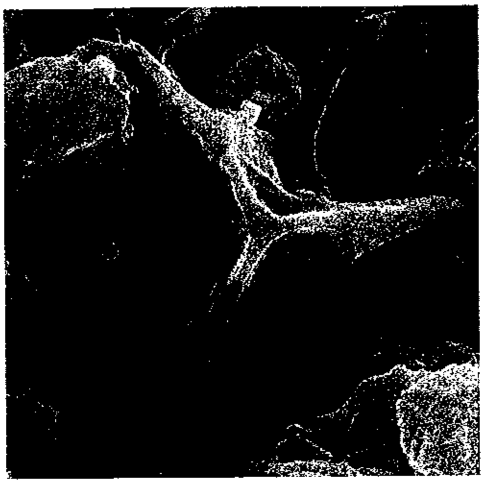
PLATE VIII

[SEM, scanning electron micrograph; XP, cross-polarized light]

Figures 1-3,6. *Rhomboaster bramlettei*
1. SEM (diameter, 12.5 µm), Zone NP 10, Island Beach 150X core (1066.9 ft), New Jersey.
2. XP (diameter, 13.0 µm), Zone NP 10, Clayton core (296.5 ft), New Jersey.
3. XP (diameter, 11.2 µm), Zone NP 10, Clayton core (296.5 ft), New Jersey.
6. XP (diameter, 17.7 µm), Zone NP 10, Clayton core (296.5 ft), New Jersey.

4,5. *Toweius occultatus*
4. SEM, distal view (length, 6.4 µm), Zone NP 13, ACGS-4 core (916.6 ft), New Jersey.
5. XP (length, 6.3 µm), Zone NP 10, Clayton core (302.5 ft), New Jersey.

7-9. *Scapholithus apertus*
7. SEM (length, 4.4 µm), Zone NP 8, K 15 core (120 ft), New Jersey.
8. XP (length, 4.7 µm), Zone NP 9, GL 915 core (130 ft), New Jersey.
9. XP (length, 4.7 µm), Zone NP 9, GL 915 core (130 ft), New Jersey.



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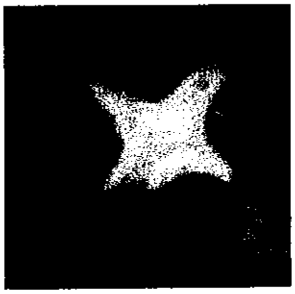

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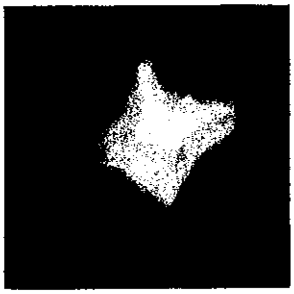

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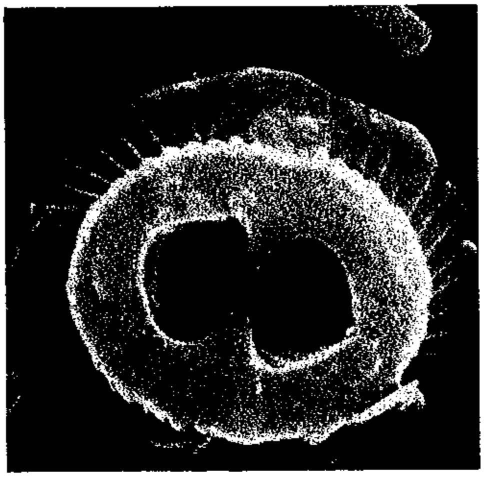

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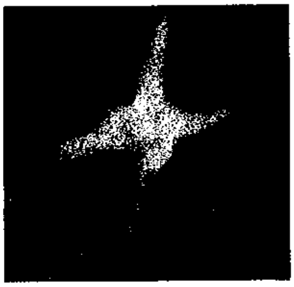

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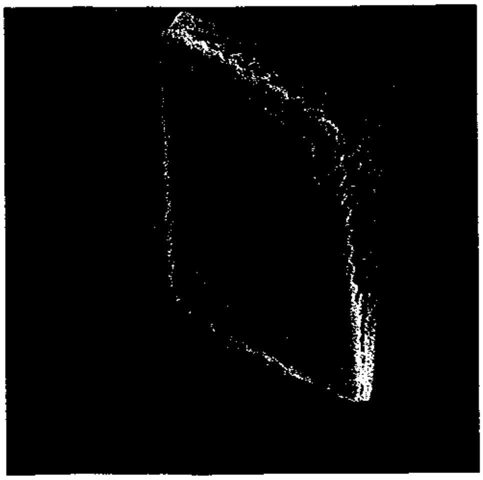

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PLATE IX

[SEM; scanning electron micrograph]

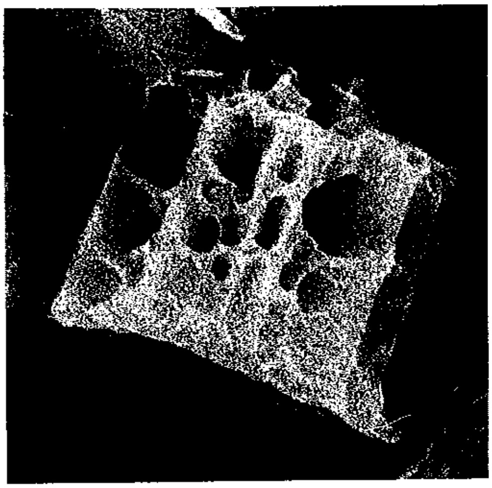
Figure 1,2. *Fasciculithus involutus*
1. SEM, side view (height, 4.5 µm), Zone NP 9, Clayton core (322 ft), New Jersey.
2. SEM, top oblique view (diameter, 6.3 µm), Zone NP 6, ASP-2 core (350 ft), New Jersey.

3. ***Hornibrookina arca***
SEM, distal view (length, 5.6 µm), Zone NP 10, Island Beach 150X core (1020.9 ft), New Jersey.

4. ***Rhomboaster contortus***
SEM (diameter, 9.0 µm), Zone NP 10, Island Beach 150X core (1018.9 ft), New Jersey.

5. ***Discoaster lodoensis***
SEM (diameter, 18.1 µm), Zone NP 13, ACGS-4 core (916.6 ft), New Jersey.

6. ***Helicosphaera seminulum***
SEM, distal view (length, 9.4 µm), Zone NP 13, ASP-2 core (234.3 ft), New Jersey.



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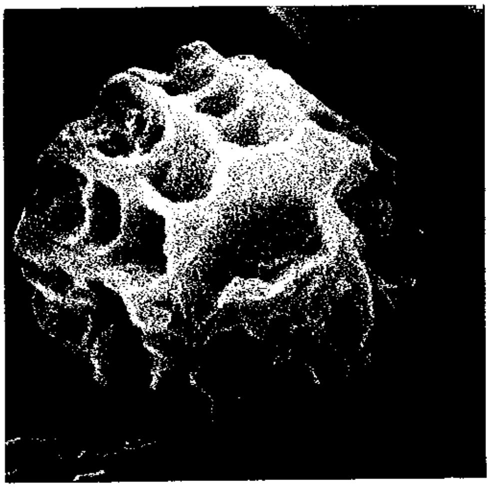

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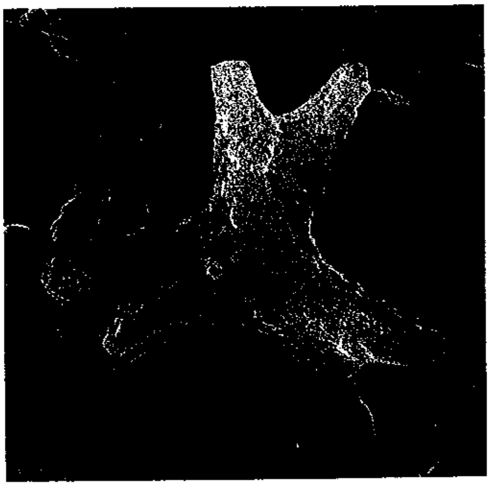

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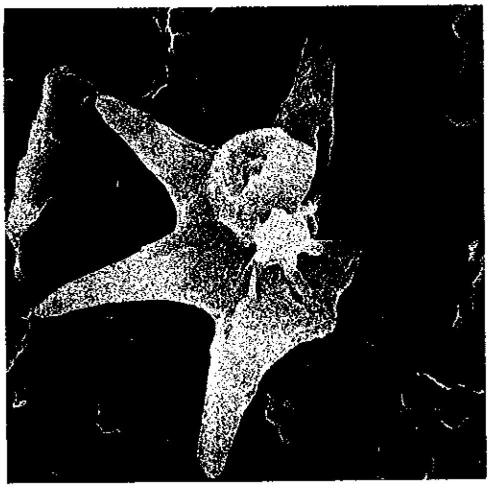

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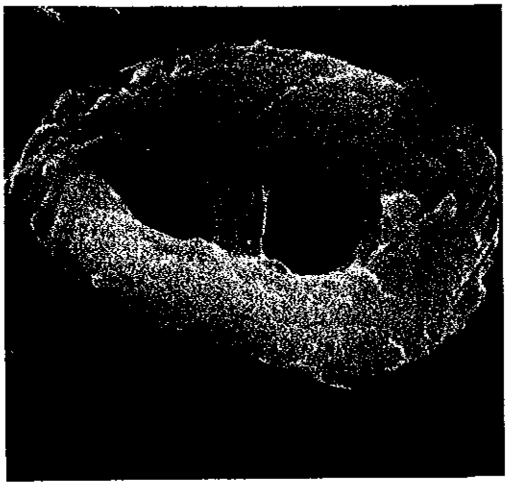

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PLATE X

[SEM, scanning electron micrograph]

Figure 1. **Helicosphaera seminulum**
SEM, proximal view (length, 10.4 µm), Zone NP 12, ASP-2 core (243.8 ft), New Jersey.

2. ***Helicosphaera lophota***
SEM, proximal view (length, 10.7 µm), Zone NP 13, ASP-2 core (234.3 ft), New Jersey.

3. ***Rhomboaster orthostylus***
SEM (width, 10.9 µm), Zone NP 11, Island Beach 150X core (1016.9 ft), New Jersey.

4. ***Discoaster sublodoensis***
SEM (diameter, 19.2 µm), Zone NP 14, ACGS-4 core (900 ft), New Jersey.

5. ***Chiasmolithus oamaruensis***
SEM, distal view (length, 11.9 µm), Zone NP 18, ACGS-4 core (766 ft), New Jersey.

6. ***Discoaster saipanensis***
SEM (diameter, 16.7 µm), Zone NP 15, ACGS-4 core (848 ft), New Jersey.

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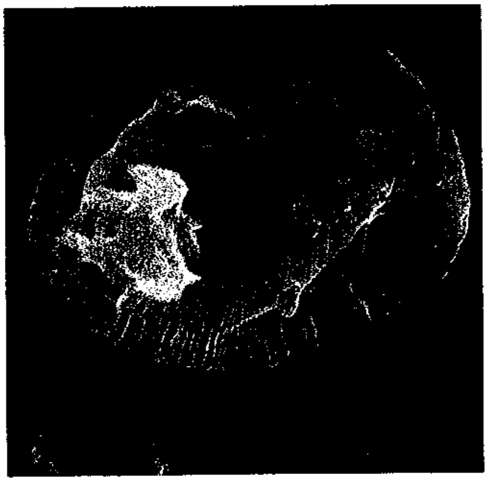

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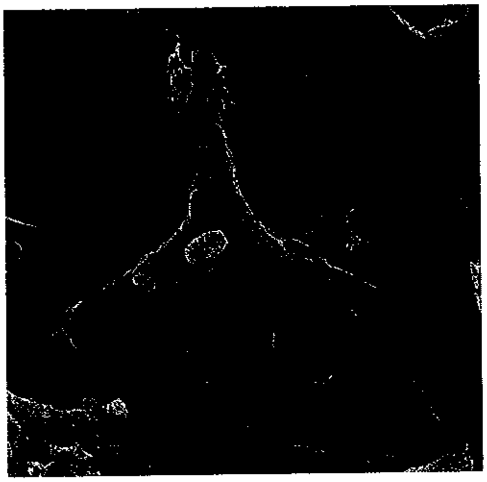

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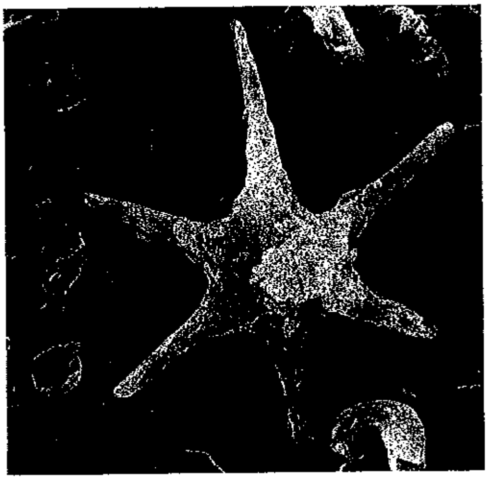

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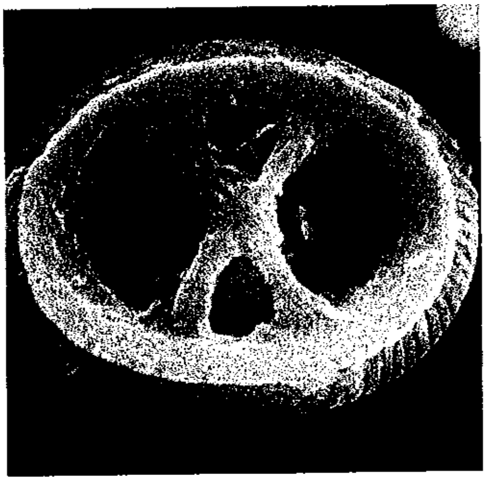

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PLATE XI

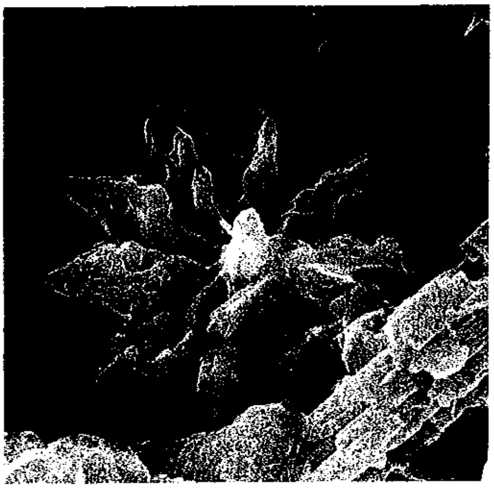
[SEM, scanning electron micrograph; XP, cross-polarized light]

Figure 1. ***Discoaster barbadiensis***
SEM (diameter, 15.6 µm), Zone NP 13, Silverton Road core (373.7 ft), New Jersey.

2,3. ***Zygrhablithus bijugatus***
2. SEM, side view (length, 7.2 µm), Zone NP 17, ACGS-4 core (784.5 ft), New Jersey.
3. XP (length, 9.9 µm), Zone NP 9, GL 913 core (125 ft), New Jersey.

4. ***Reticulofenestra umbilica***
SEM, proximal view (length, 11.2 µm), Zone NP 17, ACGS-4 core (784.5 ft), New Jersey.

5. ***Dictyococcites bisectus***
SEM, distal view (length, 11.1 µm), Zone NP 21, ACGS-4 core (629.5 ft), New Jersey.



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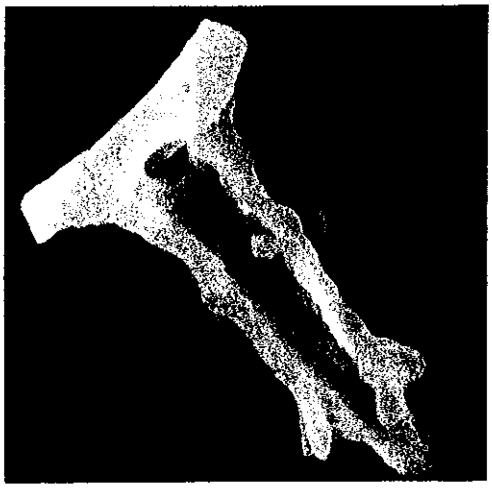

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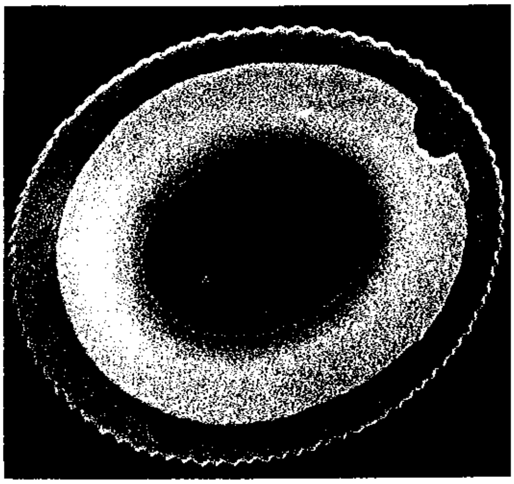

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TRIASSIC AND JURASSIC NONMARINE INVERTEBRATE TRACE FOSSILS FROM THE NEWARK BASIN, NEW JERSEY AND SOUTHEASTERN PENNSYLVANIA

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ABSTRACT

Strata representing largely lacustrine deposits of the Lockatong, Passaic, Towaco, and Boonton Formations of New Jersey and southeastern Pennsylvania have yielded an assemblage of trace fossils. Specimens include: *Biformites* isp., *Cochlichnus anguineus*, *Helminthopsis tenuis*, *Lockeia siliquaria*, *Planolites beverleyensis*, *Planolites montanus*, *Scoyenia gracilis*, *Spongeliomorpha milfordensis*, *Treptichnus bifurcus*, *Treptichnus pollardi*, and anthropod trackways. The assemblage is considered to belong to the *Scoyenia* ichnofacies.

Reddish brown siltstones and mudstones have produced almost all of the trace fossils while only a minimal mount have come from the gray and black units. Where trace fossils are diverse and abundant, field evidence indicates that a variety of paleoenvironments including lake-margin, shallow water, and floodplains with their ephemeral ponds and puddles offered optimum conditions for feeding and tracemaking. Subsequent desiccation of the sediment followed by rapid sediment influx due to flooding favored preservation of these traces. However, up section in the "redbed" sequence, produced fewer trace fossils. Longer periods of dryness coupled with limited rainfall would have severely restricted organic activity. The paucity of trace fossils in gray and black lacustrine mudstones and siltstones may be due to low oxygen conditions and/or insufficient sediment cohesiveness.

INTRODUCTION

Ichnology has been defined by Frey (1973, p.9) as the "....overall study of traces made by organisms, including their description, classification, and interpretation." These traces include trails, tracks, burrows, borings, and similar features occurring in both fossil and modern form. While the term has been employed for over 150 years, it has often been neglected compared to body fossils. Within the last three decades, however, there has been a significant increase of interest in ichnology. there are a number of reasons for this resurgence including: 1) what is preserved is both fossil as well as sedimentary structure 2) the change from a soft sediment into a rock may change or destroy body fossils, yet has little if any effect on the traces present 3) in many cases trace fossils are found preserved where body fossils are lacking (Ekdale et al., 1984). Thus when combined with other features of the substrate (e.g., physical and chemical), trace fossils have proven to be very useful in providing insight into past environments.

Studies of modern nonmarine environments indicate that a great variety of invertebrate traces, mostly by arthropods, are formed (e.g., Chamberlain, 1975; Ratcliffe and Fagerstrom, 1980; Tevesz and McCall, 1982; Metz, 1987a, 1987b). Yet some workers noted that considerably fewer of these traces are represented in fossil form (Frey et al., 1984). Frey et al. (1984) questioned whether the low diversity was due to poor preservational potential or more a lack of comprehensive study. As noted by Pickerill (1992), it certainly appears to be more of the latter. Indeed, recent studies (Frey et al., 1984; Ekdale et al., 1984; Frey and Pemberton, 1987; Sarkur and Chaudhuri, 1992; Pickerill, 1992; Buatois and Mángano, 1993b; Aceñolaza and Buatois, 1993; among others) suggest that a wide range of trace fossil assemblages existed under nonmarine conditions.

GEOLOGIC SETTING

The Newark Basin is the largest of the exposed rift basins formed along eastern North America during the breakup of Pangaea in Late Triassic to Early Jurassic time (Manspeizer, 1988; Olsen et al., 1989). This half-graben basin received thick accumulations of continental deposits spanning a period of approximately 30 million years. Although these deposits were originally thought to largely lack fossils, they have since been shown to contain one of the richest early Mesozoic faunas, especially vertebrates (Manspeizer, 1988; Olsen 1988; Olsen and Flynn, 1989; Olsen et al., 1989).

The Stockton, Locktong, Passaic, Feltville, Towaco, and Boonton Formations (Late Triassic-Early Jurassic) form the major nonmarine sedimentary units comprising the strata of the Newark Basin of New Jersey and southeastern Pennsylvania. They consist of reddish brown, gray, gray-green, and black largely lacustrine and fluvial deposits of siltstone, mudstone, and fine-grained sandstone (Olsen, 1980a). Olsen (1980a) indicated that all the sedimentary deposits above the Stockton Formation exhibit repetitive transgressive-regressive lake-level successions, designated Van Houten Cycles (Olsen, 1985), reflecting climatic modifications which affected rates of inflow versus evaporation (also see Van Houten, 1964, 1969; Smoot and Olsen, 1988).

While the geology of the formations has been extensively detailed (e.g., Van Houten, 1964, 1969; Olsen, 1980a; Smoot and Olsen, 1988; Olsen and Flynn, 1989; Olsen et al., 1989; Smoot, 1991) evidence of trace fossils have remained largely unreported (Boyer, 1979; Olsen, 1980b; Olsen et al., 1989). This paper describes the invertebrate trace fossils found within the Lockatong, Passaic, Towaco, and Boonton Formations, as part of a series of ongoing investigations by the author (Metz, 1989, 1992, 1993a, 1993b, 1995), as well as commenting on the paleoenvironment.

SYSTEMATIC ICHNOLOGY

Ichnogenus _Biformites_ Linck 1949

Biformites isp.

Plate I, figure 1

Description: Straight to curved trails, occasionally crossing, consisting of individual cylindrical segments (0.5-1.0 mm in diameter, 3-10 mm in length); each segment ending at a swollen knob-like shape. The course of the trail typically deviates slightly at each knob. In most trails, each segment exhibits a uniform width, in others there is a consistent slight flaring at one end of the cylindrical shape. Faint annulations present on many segments, are most noticeable at flared portion.
Remarks: Chamberlain (1975), Boyer (1979), and Miller and Knox (1985) indicated that the function and tracemaker of Biformites needs further definition. It has been interpreted as a dwelling burrow (Seilacher, 1955 in Häntzschel, 1975), feeding burrow of a ?worm (Chamberlain, 1971), and both a crawling and resting trace, perhaps of an arthropod (Boyer, 1979).
Occurrence: Preserved in convex hyporelief on reddish brown siltstone (Boonton Formation, Boonton, NJ; Passaic Formation, Milford, NJ).

Ichnogenus Cochlichnus Hitchcock 1858

Cochlichnus anguineus Hitchcock 1858

Plate I, figure 2

Description: Smooth, unlined, sinusoidal, unbranched, horizontal burrows (0.5-2.0 mm in diameter, visible lengths up to 2 cm).
Remarks: Cochlichnus represents a crawling trace (Pienkowski, 1985; Eagar et al., 1985) created by worms or worm-like organisms (Hitchcock, 1858; Eagar et al., 1985). Moussa (1970) noted seeing a nematode forming a similar appearing form, while Metz (1987c) indicated that biting midge larvae were capable of forming modern sinusoidal Cochlichnus-like traces around the margin of ponds and small streams. Undulating movements by the larvae produced these wave-like trails as they progressed over a mud surface covered by a thin film of water.
Occurrence: Preserved in convex hyporelief on reddish brown fine-grained siltstone (Towaco Formation, Lincoln Park, NJ) and reddish brown mudstone (Passaic Formation, Milford, NJ; Lockatong Formation, Gwynedd, PA).

Ichnogenus Helminthopsis Heer 1877

Helminthopsis tenuis Książkiewicz 1968

Plate I, figure 3

Description: Smooth, narrow, straight to gently winding or meandering constant diameter burrows (0.5 mm or 1.0 mm), maximum length 8 cm. Individual burrows do not exhibit level crossings; burrow fill is similar in grain size to surrounding sediment.
Remarks: Possible producers include a worm (Chamberlain, 1971) or worm-like form (Miller and Knox, 1985), polychaetes or priopulans (Książkiewicz, 1977), or nematodes and arthropods under nonmarine conditions (Buatois and Mángano, 1993b).
Occurrence: Preserved in concave epirelief and convex hyporelief on reddish brown mudstones (Passaic Formation, Milford, NJ; Towaco

Formation, Lincoln Park, NJ).

Ichnogenus Lockeia James 1879

Lockeia siliquaria James 1879

Plate I, figure 4

Description: Small (1-5 mm in length, diameter 0.5-1.0 mm) mostly almond, a few tear-shaped traces. Some specimens show evidence of growth lines.
Remarks: The majority of workers (e.g., Seilacher, 1953; Osgood, 1970; Hallam, 1970; Hakes, 1977; Kamola, 1984) have interpreted these almond-shaped traces to have resulted from resting bivalves. In addition, a few workers have cited branchiopod crustaceans as the possible producer of some Lockeia (Bromley and Asgaard, 1972, although subsequently rejected by them [Bromley and Asgaard, 1979]; Pollard, 1981; Metz, 1989; Pollard and Hardy, 1991). The presence of branchiopods within the Passaic and Lockatong Formations could certainly account for a portion of these almond-shaped traces.
Occurrence: Preserved in concave epirelief and convex hyporelief on reddish brown siltstones (Passaic Formation, Milford, NJ; Lockatong Formation, Gwynedd, PA).

Ichnogenus Planolites Nicholson 1873

Planolites beverleyensis (Billings 1862)

Plate I, figure 5

Description: Simple, mostly straight to gently curved, unbranched, horizontal to sub-horizontal, generally smooth-walled, circular to ellipsoidal unlined burrows. Diameter 2.5-10.0 mm, preserved length up to 5 cm. Structureless burrow filling is coarser than the surrounding rock. Individual burrows, as well as multiples which interpenetrate or cross each other are present. A few specimens exhibit faint evidence of annulations.
Remarks: A combination of the longer size, near constant diameter in clastic sediments, and more gentle curving of the burrows distinguishes P. beverleyensis from P. montanus (Pemberton and Frey, 1982). In addition, branching is slightly more common in P. montanus (Howard and Frey, 1984).
Occurrence: Preserved in convex hyporelief on reddish brown siltstones and sandstones (Passaic Formation, Milford, NJ; Towaco Formation, Pompton, NJ) and reddish brown mudstones (Boonton Formation, Boonton, NJ)

Ichnogenus Planolites Nicholson 1873

Planolites montanus Richter 1937

Plate I, figure 6

Description: Simple, smooth, unbranched, mostly horizontal, straight

to curved burrows (0.5-1.5 mm in diameter). Crossovers and interpenetrations of burrows are common. Burrows are unlined, filled with coarser sediment than the surrounding rock.
Remarks: Pemberton and Frey (1982) envisioned a free moving, deposit-feeding organism, perhaps a polychaete, as being responsible for Planolites, while Buatois and Mángano (1993b) noted that arthropods may be responsible under nonmarine conditions. However, due to its simple form, broad range (Precambrian to Holocene), and facies-crossing characteristic, a variety of animal species may be responsible (Pickerill et al., 1984; Crimes and Anderson, 1985).
Occurrence: Preserved in convex hyporelief on reddish brown siltstones and sandstones (Towaco Formation, Lincoln Park and Pompton, NJ) and reddish brown sandstones (Lockatong Formation, Arcola, PA)

Ichnogenus Scoyenia White 1929

Scoyenia gracilis White 1929

Plate II, figures 1-3

Description: Straight to gently curved burrows, 1-15 mm in diameter (each one retaining a nearly consistent size), preserved length up to 13 cm. Burrows possess distinctive longitudinal striations which parallel or bend toward each other, are parallel or oblique to the bedding surface, with crossovers being somewhat common. Weathered specimens exhibit wall linings as well as poorly sorted meniscate fill, some menisci containing "pellet-like" forms.
Remarks: Scoyenia is the most common trace fossil within the nonmarine sedimentary deposits of the Newark Basin (Smoot and Olsen, 1988). Frey et al. (1984) in providing an in-depth review of this ichnogenus, concluded that Scoyenia represents a feeding burrow formed by an arthropod. Sediment was likely ingested and sorted within its gut, while other materials passed around itself were sorted by body movements and appendages. In addition, D'Alessandro et al. (1987) suggested a specialized insect or polychaete, while Olsen (1977) proposed that a decapod crustacean was responsible for this trace.

The overall presence and sharpness of the exterior striations indicates an organism which for the most part was in close contact with the surrounding sediment. In addition, the sediment size and degree of saturation was such so as to allow the appendages to impart the sharp incisions that are found. However, due to the individual length and overall longitudinal appearance of these striations, I believe that the appendages responsible for such were not actively involved in burrow "excavation" in itself, but were dragged along by the animal as it moved. Furthermore, other evidence indicates that the animal apparently did not always burrow. Interruption of striation evidence on some bedding surfaces may point to animal movement through very shallow aquatic conditions with only occasional contact of the appendages with the sediment surface.
Occurrence: Preserved in convex and concave hyporelief on reddish brown siltstones and mudstones (Passaic Formation, Milford, NJ; Towaco Fromation, Roseland, NJ), reddish brown mudstones (Lockatong Formation, Chalfont, Gwynedd, and Arcola, PA), as well as several on dark gray mudstones (Lockatong Formation, Chalfont, PA).

Ichnogenus Spongeliomorpha Saporta 1887

Spongeliomorpha milfordensis Metz 1993a

Plate II, figures 4-5

Description: Horizontal, mostly straight to slightly curved unlined burrows displaying incised partial wall striations, majority crossing each other, individual striae forming acute angle with the axis of the burrow. Occasionally specimens exhibit branching. Burrows are cylindrical to ellipsoidal, 1-6 mm in diameter, maximum length up to 12 cm; structureless burrow fill is similar to the enclosing sediment.
Remarks: Saporta (1887) proposed Spongeliomorpha iberica for mostly longitudinally striated burrows from Miocene marine deposits of Spain. Bromley and Asgaard (1979) introduced Steinichnus carlsbergi for a distinctive trace fossil from the nonmarine Triassic of East Greenland, which later was assigned to Spongeliomorpha carlbergi (see Ekdale et al., 1984; Bromley and Asgaard, 1991). Subsequently, Metz (1993a) erected Spongeliomorpha milfordensis as an additional nonmarine example from the Jurassic of New Jersey. Various interpretations have been made regrarding the organism responsible for Spongeliomorpha (e.g., sponges [Saporta, 1887], callianassid excavations [Fürsich, 1973; Flor et al., 1979]). Metz (1993a) agreed with Bromley and Asgaard (1979) that it was likely an insect form, in this case a nonmarine deposit-feeding aquatic insect larvae.
Occurrence: Preserved in convex and concave hyporelief, and convex epirelief on reddish brown siltstones and sandstones (Passaic Formation, Milford, NJ), reddish brown siltstones (Boonton Formation, Boonton, NJ), reddish brown mudstones (Lockatong Formation, Chalfont and Gwynedd, PA), and several on medium gray mudstones (Lockatong Formation, Chalfont and Gwynedd, PA).

Ichnogenus Treptichnus Miller 1889

Treptichnus bifurcus Miller 1889

Plate III, figure 1

Description: Straight to curved burrow trace (1 mm in diameter), with short extensions (1-2 mm) possessing slightly thickened rounded terminations projecting from junctures between longer segments, creating a zigzag pattern.
Remarks: Similar to the emended description by Maples and Archer (1987), where the present trace is mostly straight, extensions occur on alternate sides; where curved, extensions occur on outside of curved portion.
Occurrence: Preserved in convex hyporelief on reddish brown mudstones (Towaco Formation, Roseland, NJ).

Ichnogenus Treptichnus Miller 1889

Treptichnus pollardi Buatois and Mángano 1993a
Plate III, figures 2-3

Description: Specimens consist of straight, zigzag, or curved burrow segments possessing pits, representing openings of vertical shafts, situated either at juncture or at some position within individual segments. Burrow diameter varies between 0.5-1.5 mm, while individual segments range from 3 to 22 mm. Variable burrow systems commonly crossing or parallel to each other; individual systems generally exhibiting linear or polygonal shape. The maximum number of burrow segments in a system is 7; most systems have 5 or less.
Remarks: Maples and Archer (1987) redescribed the type material of Treptichnus, while Buatois and Mángano (1993a) provided an in-depth reevaluation of this ichnotaxon, including the naming of T. pollardi, based on a well preserved assemblage found in Carboniferous lacustrine rocks of northwestern Argentina. Treptichnus has been interpreted to represent a feeding structure formed by vermiform animals (Buatois and Mángano (1993a).
Occurrence: Preserved in concave and convex hyporelief on reddish brown siltstones and mudstones (Lockatong Formation, Gynedd, PA).

Trackways

Plate II, figure 4

Three individual trackways on desiccation-cracked surface.

Description: Double row of straight to slightly curved tracks, approximately 3 mm in diameter, represented by small (0.5-1.0 mm in diameter) rounded to oval protuberances. Within each row, protuberances may exhibit variation in their position relative to the axis of the trackway: 1) singular ones trending parallel to the axis 2) multiple protuberances parallel to each other and the axis, or forming angle with each other and the axis. One trackway exhibits slightly curved slashes, 1mm in length, oriented approximately normal to the axis, along the outside portion of one row of protuberances.
Remarks: The three examples have been grouped together due to the presence of protuberances and the consistent width of each trackway. Due to variable preservation, both singular and double rows of protuberances are visible along the trackways. The trackways are interpreted to have been formed by an arthropod, probably an insect.
Occurrence: Preserved in convex hyporelief on reddish brown siltstone (Towaco Formation, Towaco, NJ).

Plate III, figure 5

Description: Single, simple, straight to curved trackway, approximately 2.5 mm in diameter, consisting of two rows of linear traces elongated parallel to the direction of movement.
Remarks: Interpreted as insect trackway. Trace is somewhat similar to the ?insect trackway Acanthichnus (Hitchcock, 1858).

Occurrence: Preserved in convex hyporelief on reddish brown mudstone (Towaco Formation, Towaco, NJ).

Plate III, figure 6

Description: Single, straight trackway, approximately 5 mm in diameter. Consists of a double row of outer and inner imprints. The outermost imprints are short, straight to cresent-shaped furrows which are nearly normal to an innermost set, consisting of linear traces, 1 mm apart, elongated parallel to the direction of movement.
Remarks: The trackway is similar to the traces Siskemia and Protichnites which have been attributed to arthropod forms. The present trace is likely of similar origin.
Occurrence: Preserved in concave epirelief on reddish brown mudstone (Lockatong Formation, Gwynedd, PA).

DISCUSSION

Seilacher (1967) designated the Scoyenia ichnofacies to represent distinctive trace fossils found in nonmarine shales and sandstones (commonly redbeds). However, Seilacher (1987) indicated that a real problem existed in recognizing nonmarine conditions. Redbeds typically produced a low diversity of trace fossils, not one of which was by itself indicative of nonmarine conditions. Indeed, investigations have show that certain "exclusive" marine trace fossils have been found in unequivocal nonmarine strata, and vice-versa. Frey et al. (1984) suggested that the Scoyenia ichnofacies was but one of a wide range of possible trace fossil assemblages that existed under nonmarine conditions. They further indicated that the Scoyenia ichnofacies be restricted to one characterized by a low diversity of traces formed in moist or wet sediment intermittently exposed to air, and dominated by Scoyenia gracilis, Ancorichnus coronus or their ethologic and morphologic equivalents.

Investigation of the Newark Basin strata of New Jersey and southeastern Pennsylvania indicates that the reddish brown siltstones and mudstones have yielded almost all of the trace fossils while only a minimal amount have come from the gray and black units. Associated sedimentary structures often include desiccation cracks, ripple marks, tool marks, crossbedding, and raindrop impressions. Where trace fossils are diverse and abundant, field evidence indicates that a variety of paleoenvironments including newly exposed lake-margins, shallow water deposits, as well as floodplains with their associated ephemeral ponds and puddles, offered optimum conditions for inhabitation and feeding by various small-sized opprotunistic arthropods (e.g., insects/insect larvae). Desiccation eventually followed as evidenced by the mudcracking, and in the process hardened many of the previously formed traces. Subsequent flooding due to rainstorms provided rapid sediment influx which covered the burrows, trails, and tracks. Investigation further up section within the "redbed" sequence, however, typically produced fewer trace fossils and far less numbers of each form. Longer periods of dryness only occasionally punctuated by smallscale rainfall would have resulted in limited sediment moisture and nutrients, thereby restricting organic activity.

The paucity of trace fossils within gray and black lacustrine mudstones and siltstones may be due to the higher organic content (representing lake high stand of Olsen, 1989), which could have created anoxic bottom conditions thereby limiting most benthonic organisms (Olsen, 1980b; Manspeizer, 1988). In addition, the presence of organic detritus would have, in effect, lowered the degree of cohesiveness of the surface sediment.

Burrowing forms dominated by _Scoyenia gracilis_ or its ethologic equivalents are the most abundant trace fossils found in Newark Basin strata. This, combined with low to moderate diversity in which trace-making largely occurred in moist to shallow water conditions subject to periodic exposure, allows the trace fossil association present in strata of the Newark Basin of New Jersey and southeastern Pennsylvania to be characterized as a _Scoyenia_ ichnofacies, following suggestions by Seilacher (1967), Frey et al. (1984), and Frey and Pemberton (1987).

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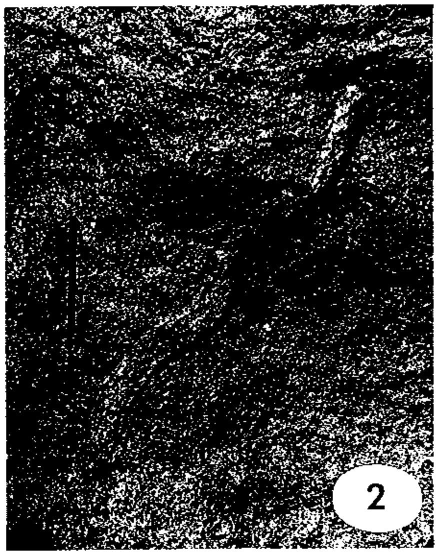
Plate I. Ichnotaxa of the *Scoyenia* ichnocoenosis. (1) *Biformites* isp. (2) *Cochlichnus anguineus*. (3) *Helminthopsis tenuis* (arrows). (4) *Lockeia siliquaria* (5) *Planolites beverleyensis*. (6) *Planolites montanus*. Scale for figures (1-6) = 5 mm. Specimens preserved in convex and concave relief. After Metz, 1989, 1992, 1993b.

Plate II. Ichnotaxa of the *Scoyenia* ichnocoenosis. (1-2) *Scoyenia gracilis* preserved in convex relief. (3) Weathered specimen of *Scoyenia gracilis* illustrating meniscate fill, preserved in convex relief. (4) *Spongeliomorpha milfordensis*. (5) *Spongeliomorpha milfordensis* showing acute angle of branching. Scale for figures (1, 3-5) = 5 mm, for figure (2) = 1 cm. All specimens preserved in convex relief. After Metz, 1993a, 1995.

Plate III. Ichnotaxa of the *Scoyenia* ichnocoenosis. (1) *Treptichnus bifurcus*. (2-3) *Treptichnus pollardi* illustrating zigzag and parallel burrow segments with pits (2), and curved segments with pits (3). (4) Insect trackways. (5) Insect trackway. (6) Trackway likely formed by an arthropod. Scale for figures (1-6) = 5 mm. Specimens preserved in convex and concave relief. After Metz, 1992, 1995.

Pl. I


1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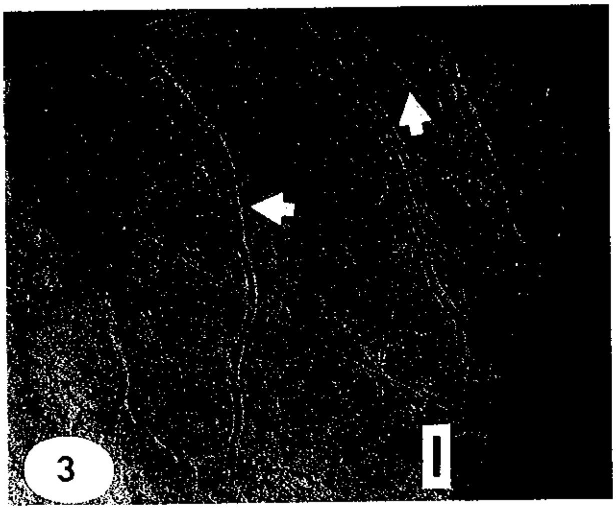
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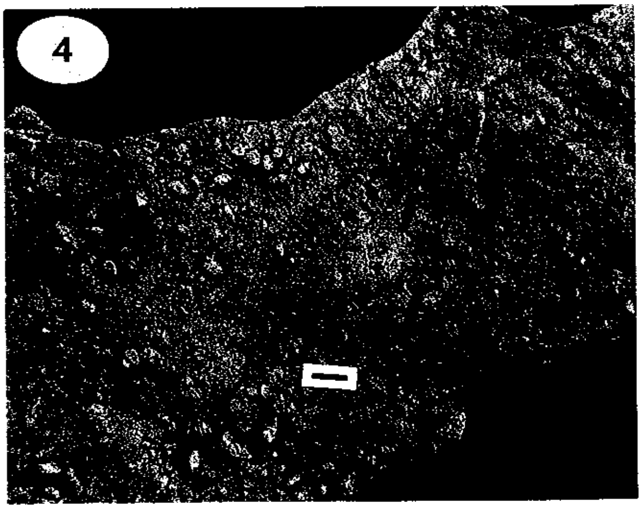
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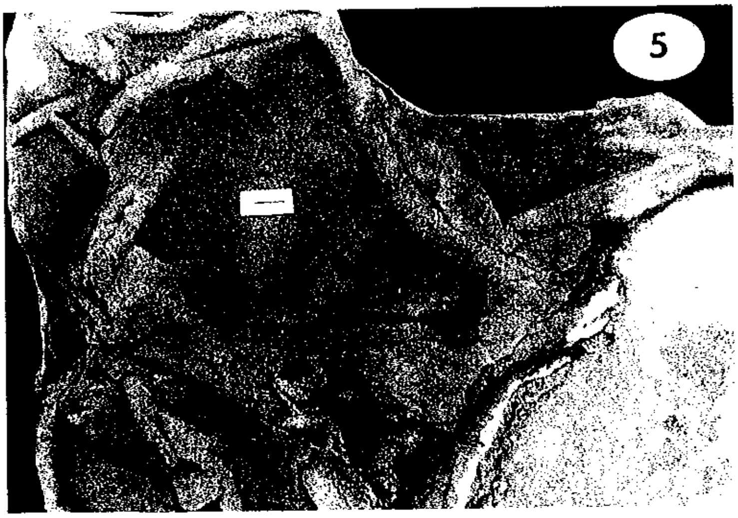
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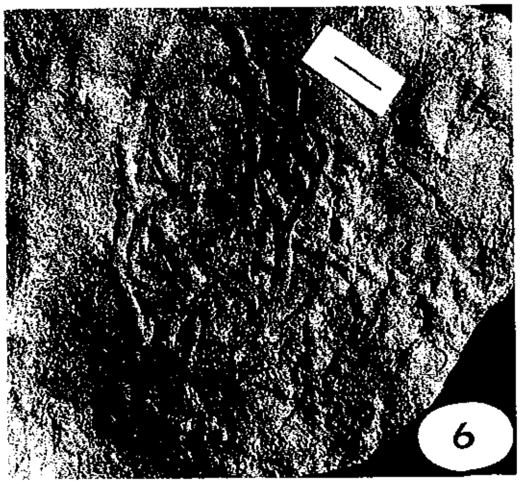
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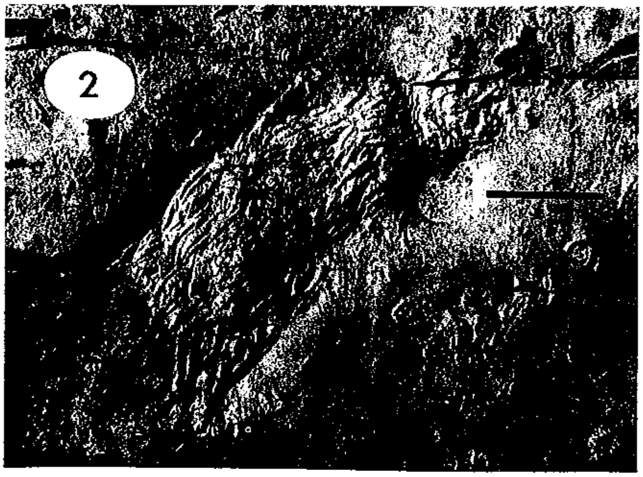
Pl. II


1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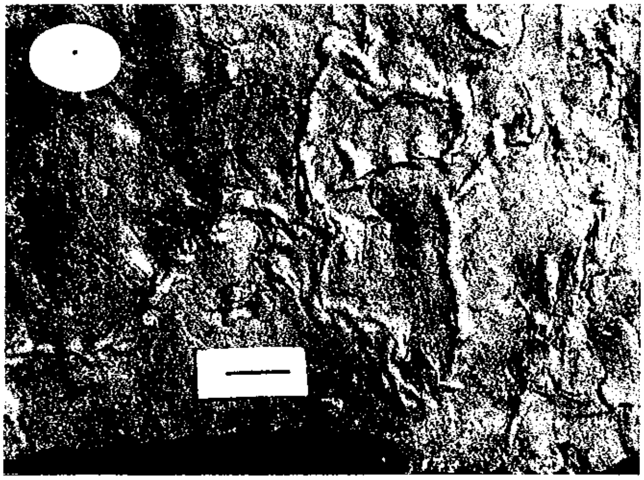
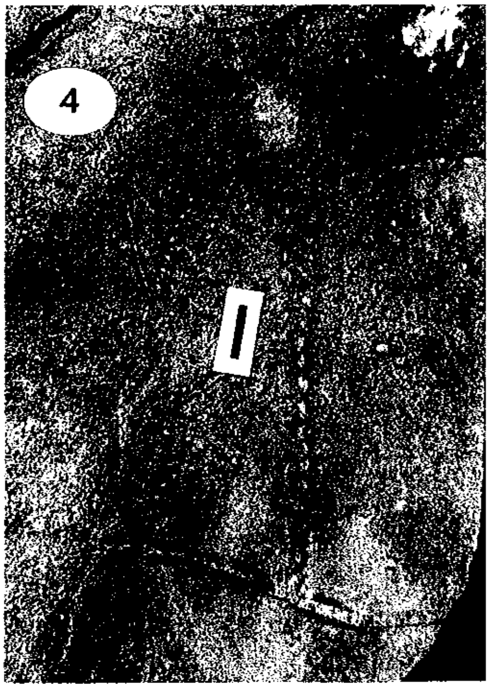
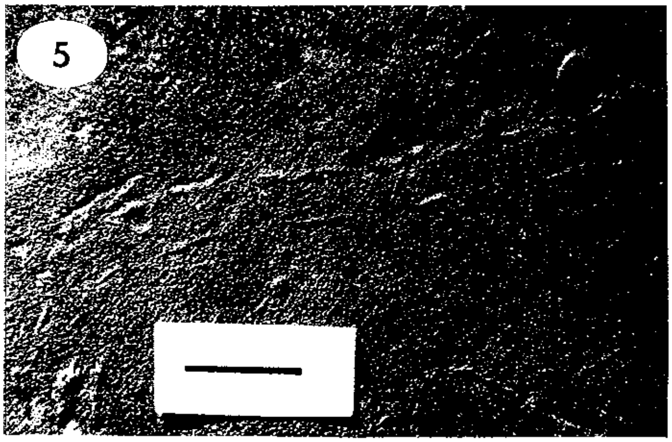
4


5

Pl. III







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

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INTRODUCTION

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

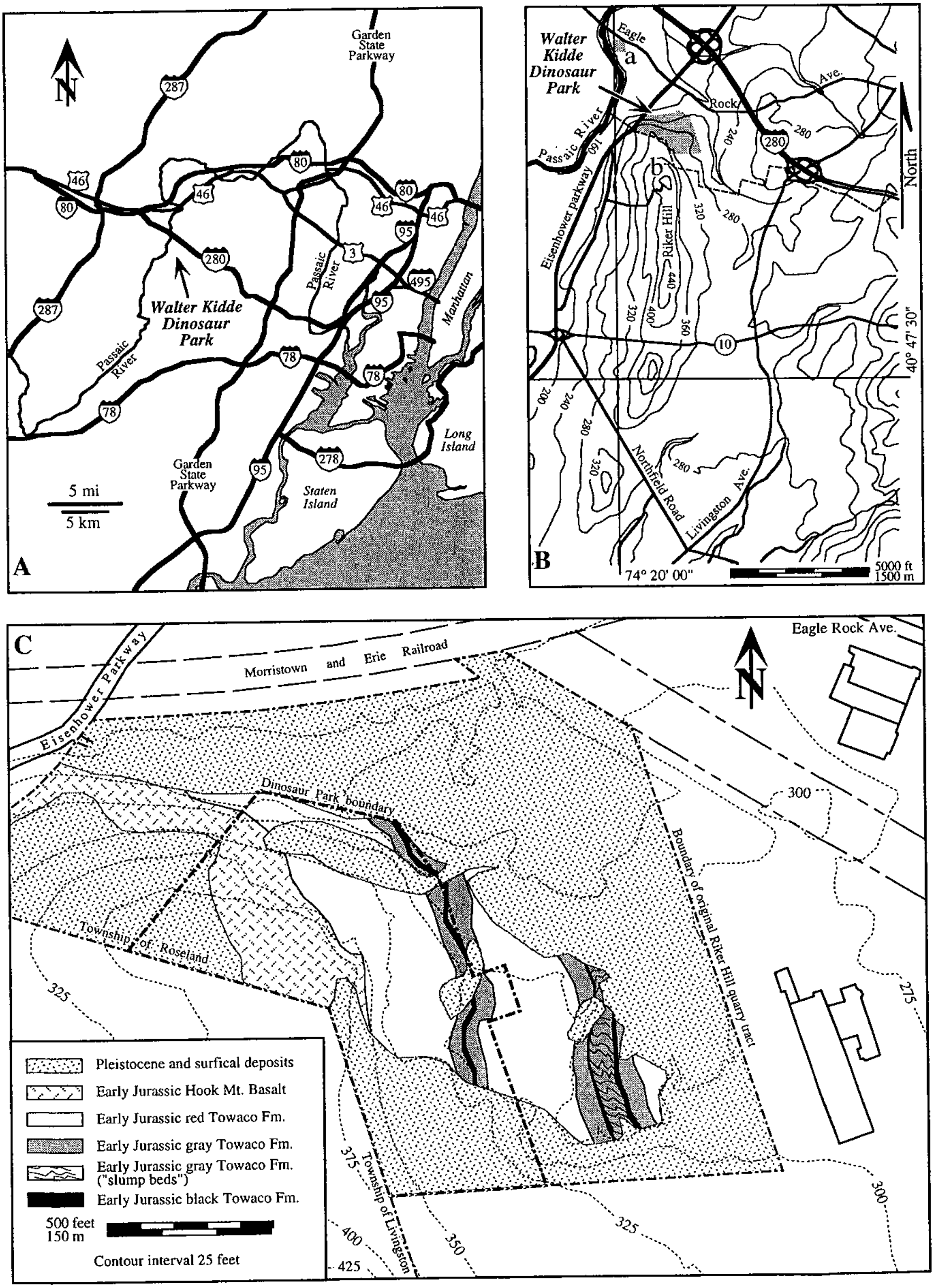
HISTORY OF COLLECTION

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

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

GEOLOGICAL CONTEXT

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


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

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

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

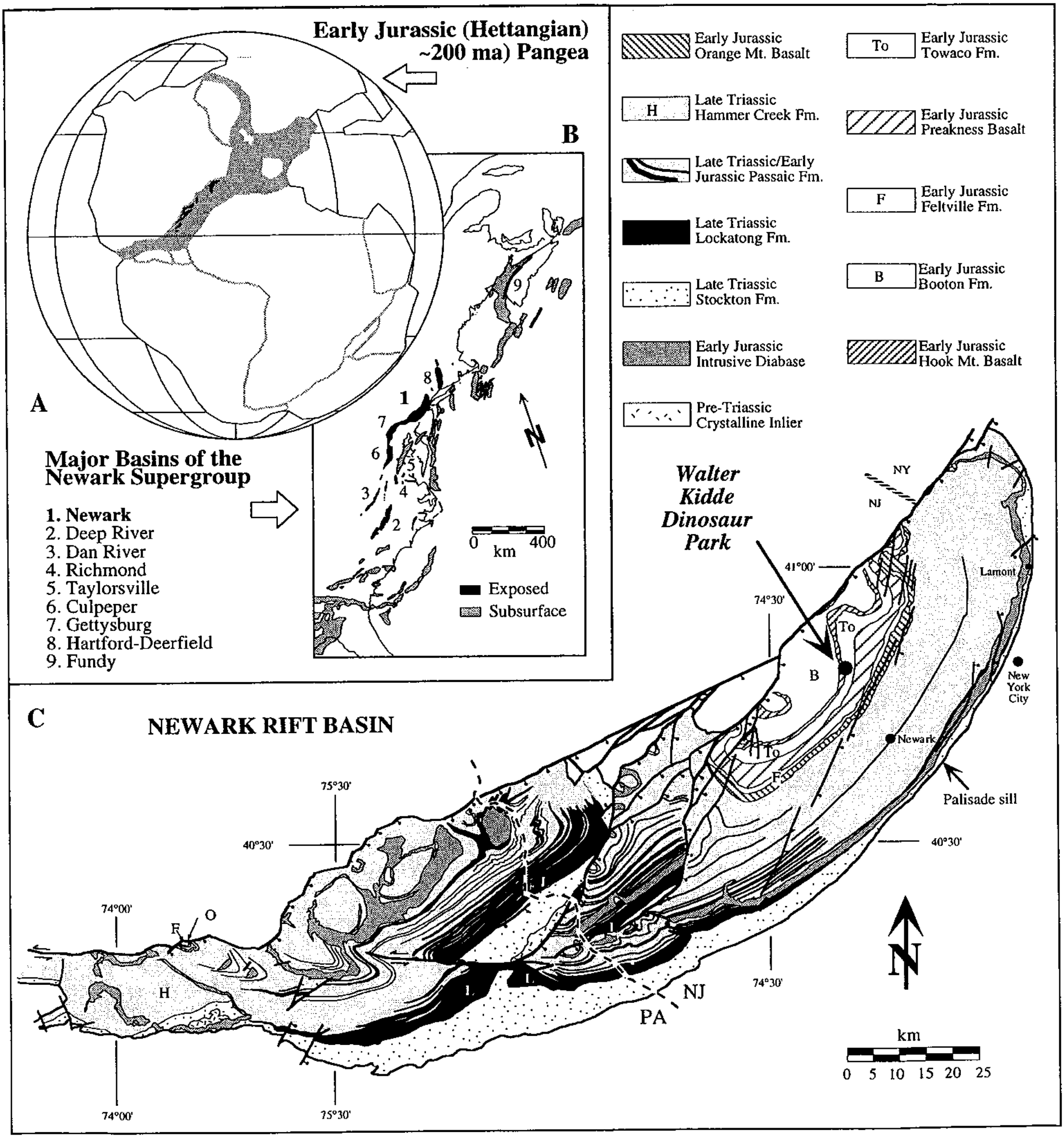
The Towaco Formation at the Roseland Quarry consists of relatively fine-grained red, gray, and black units, mostly mudstone and fine sandstone. This facies represents some of the more basinward deposits of the Newark basin Jurassic, although the sequences deposited near the geographic center of the basin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

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

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

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

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


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

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

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

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

PALEONTOLOGY

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

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

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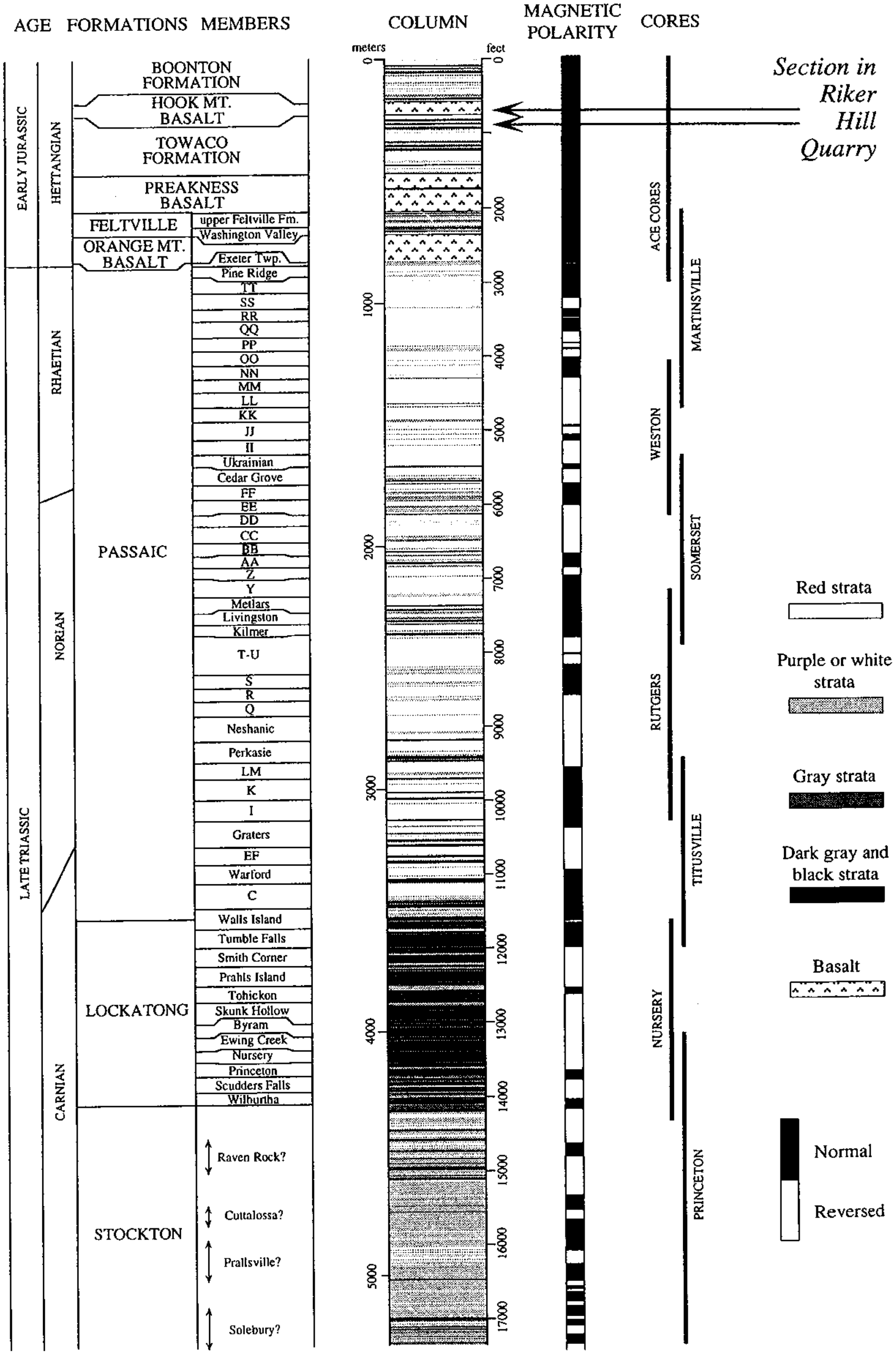
Figure 2. Geological context of the Water Kidde Dinosaur Park. **A**, Configuration of the supercontinent of Pangea in the earliest Jurassic, based on Witte and Kent (1990) and data in Kent and others (1995). Gray area shows region of extensive early Mesozoic rifting, and the black regions are the preserved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

NEWARK BASIN SECTION



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

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

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

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

Kingdom Monera

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

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

Kingdom Protoctista
PHYLUM CHLOROPHYTA (green algae)

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

Kingdom Plantae (multicellular green plants)
PHYLUM SPHENOPHYTA (horse tail rushes and quillworts)
Equisetites sp.

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

PHYLUM PTERIDOPHYTA (ferns)
Organ taxa *Cladophlebis* sp., *Clathropteris sp.*, *Dictyophyllites* sp.,
Converrucosisporites cameronii

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

PHYLUM CONIFEROPHYTA (conifers)
Cheirolepidaceae
Organ taxa *Pagiophyllum* spp., *Brachyphyllum* spp. (in part),
Corollina meyeriana

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

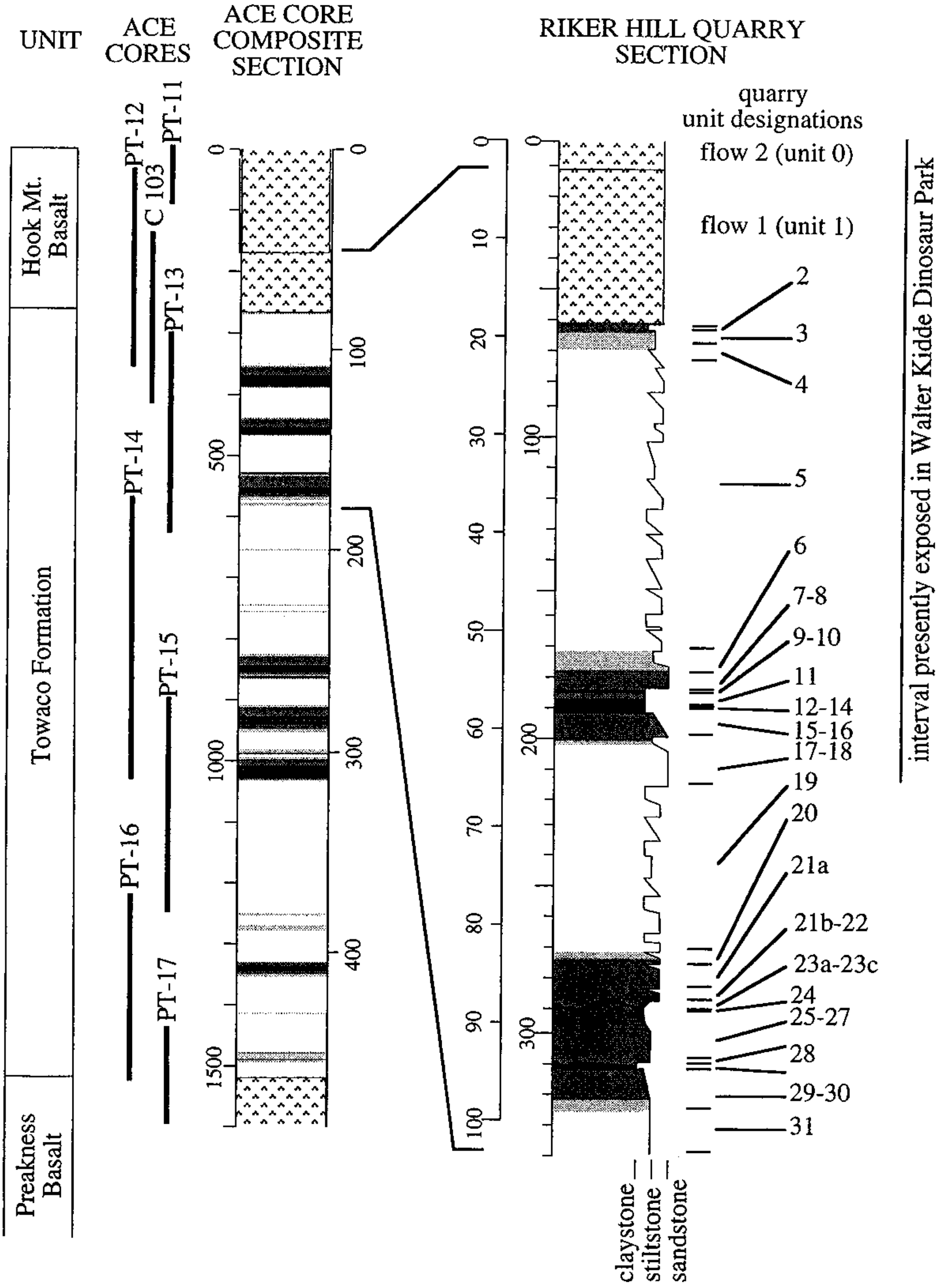
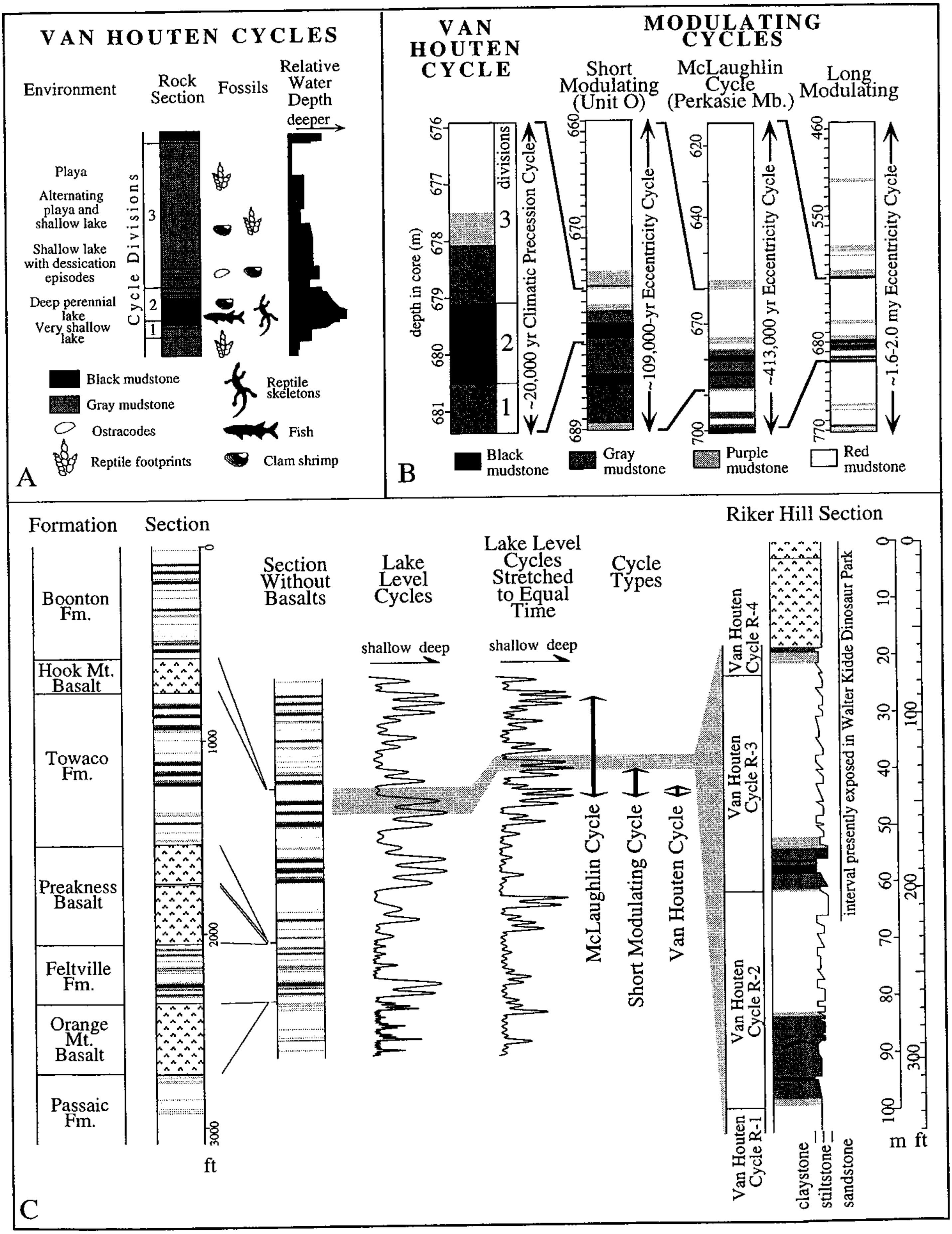


Figure 4. Section in old Riker Hill quarry compared to reference section of the Towaco Formation from the Army Corps of Engineers cores; from Olsen and others (1995b). Unit designations are referred to in text. Key to lithologies as in figure 3. Original quarry section described in Olsen (1975).


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

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

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

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

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

Araucariacae (monkey puzzle tree and relatives)
Organ taxa *Brachyphyllum* spp. (in part), *Araucariacites australis* (pollen)

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

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

PHYLUM CYCADOPHYTA (cycads and cycad-like seed plants)

Organ genera *Otozamites* sp., *Cycadopites* sp.

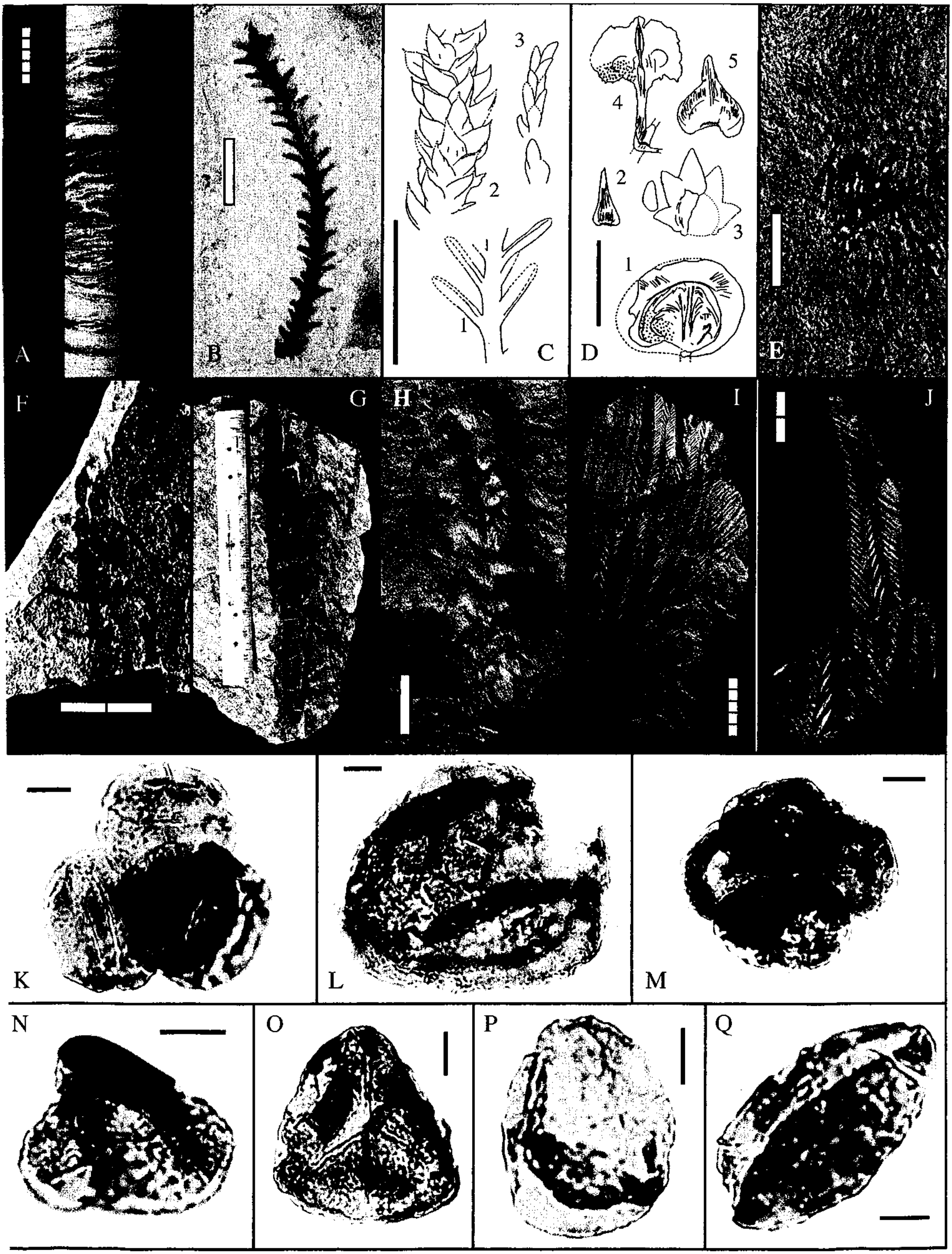
The Cycadophyta are a group of plants including the extinct Bennettitales and the superficially similar extant cycads. Rare elongate triangle-shaped leaves attributable to the Cycadophyte foliage genus *Otozamites* have been found in the Dinosaur Park in unit 10 of cycle RVH-3. These leaves resemble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

Kingdom Animalia *incertae sedis* (uncertain classification)

Ichnotaxa *Cochlichnus anguineus, Helminthopsis* sp., *Planolites montanus, Planolites beverleyensis Trepyichnus bifircus, Biformites* sp., *Fustiglyphus roselandensis, Scoyenia gracilis*

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

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


A
B
3
2
1
C
4
5
2
3
1
D
E
F
G
H
I
J
K
L
M
N
O
P
Q

of linked trails: a thin (0.4-0.6 mm) part 4-7 mm long with distinct annulations and a thicker (2-2.5 mm) part 2 to 3 mm long with faint annulations. There is a faint grove running down the middle of the trace. *Biformites* is a tapering trace with annulations and a faint longitudinal groove. According to Boyer (1979) the Roseland *Fustiglyphus* is a succession of repeated *Biformites* -like traces, probably produced by a small arthropod seeking refuge in a deteriorating environment.

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

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

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

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

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

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

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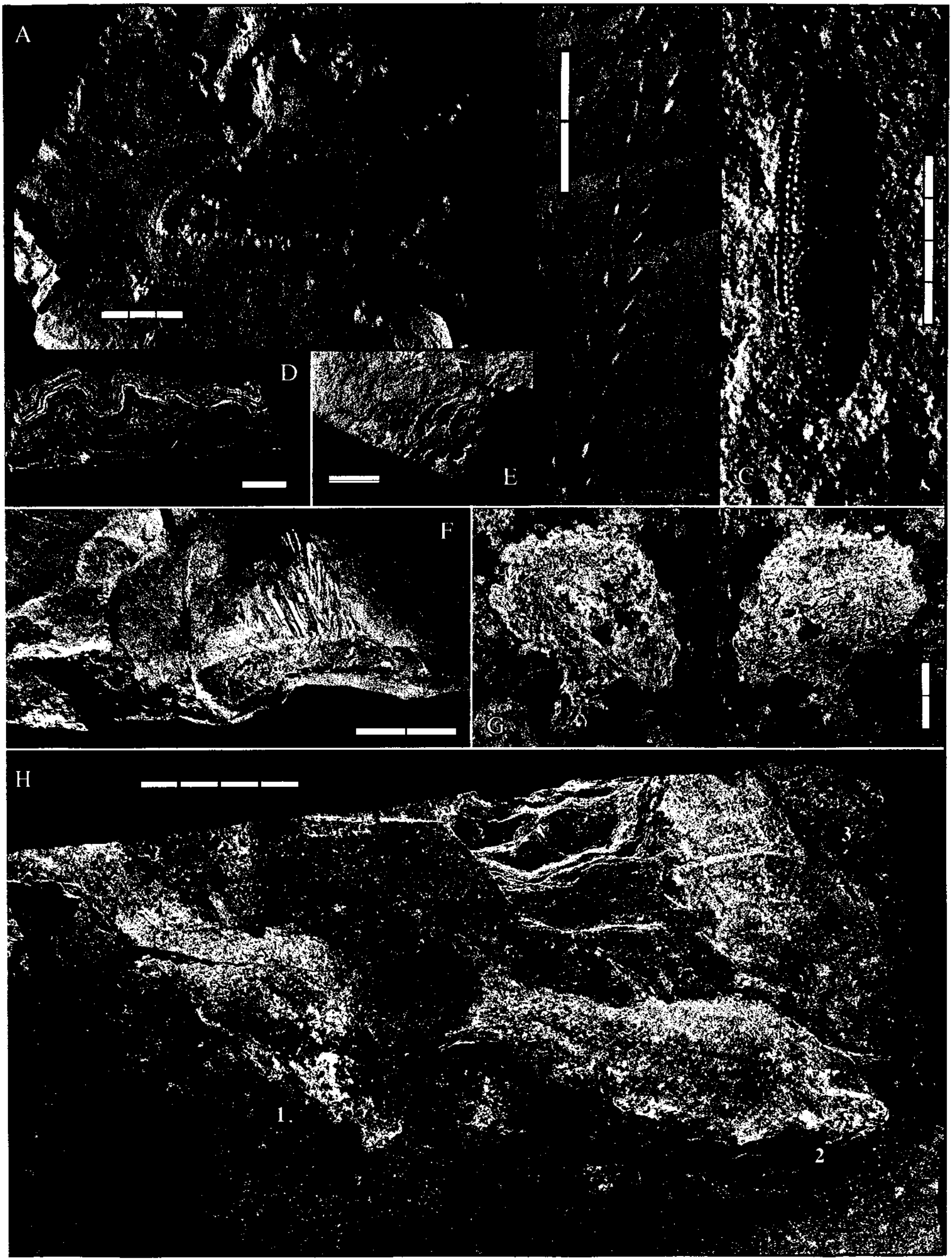
Figure 7. Invertebrates and fish from the Riker Hill Quarry. **A**, unusual, unidentified burrow (scale, 3 cm) from unit 5, Dinosaur Park; **B**, insect walking trace, *Acanthichnus* sp., from low in unit 5, Dinosaur Park; **C**, beetle elytron (wing cover), *Liassocupes* sp., unit 10, Dinosaur Park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

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

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

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

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

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

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

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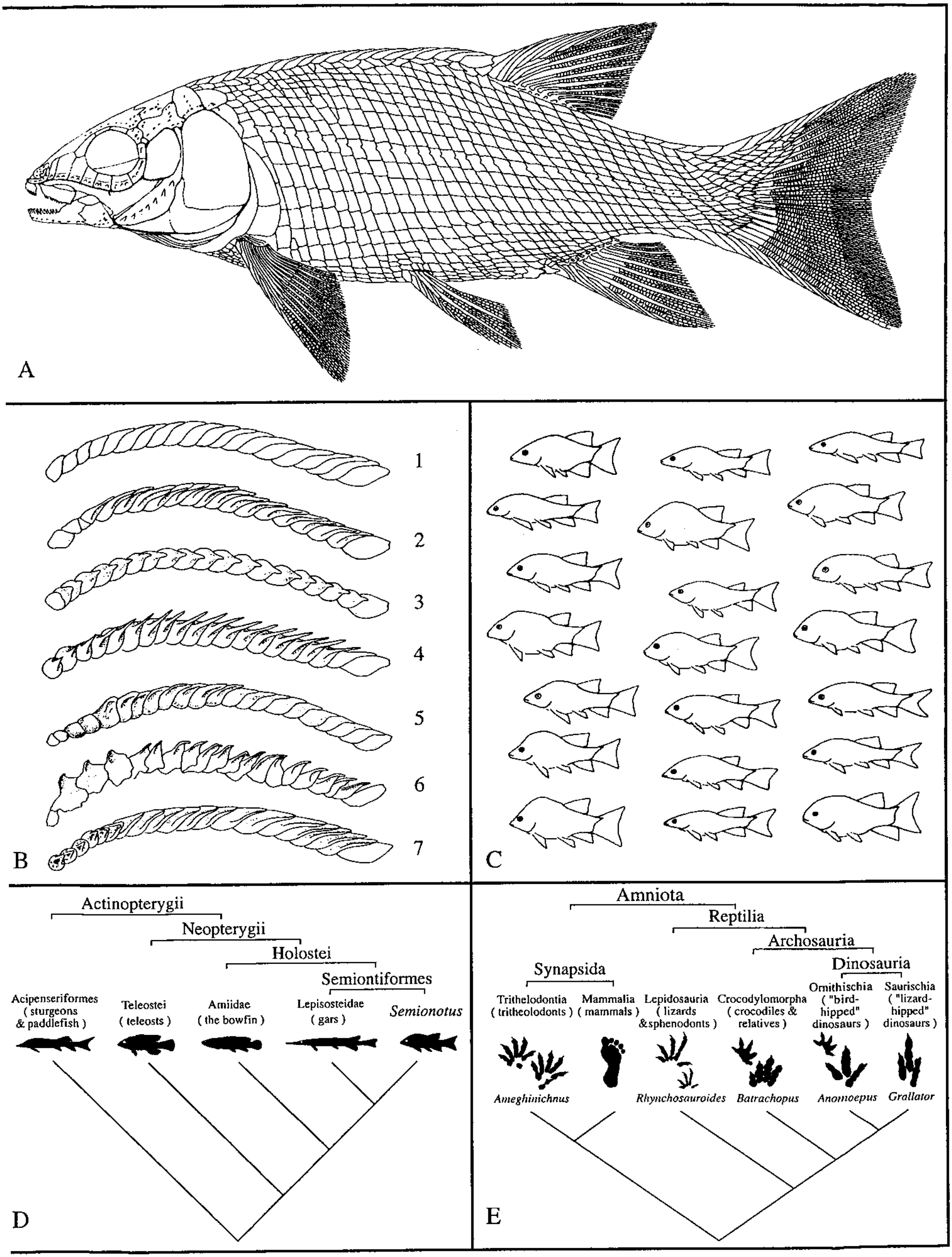
Figure 8. *Semionotus*, fish relationships and tetrapod relationships for the Riker Hill quarry. **A**, Reconstruction of member of the *Semionotus elegans* group of *Semionotus* from the Boonton Formation of Boonton, NJ (from Olsen and McCune, 1991), the form of which is representative of Riker Hill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

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

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

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

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

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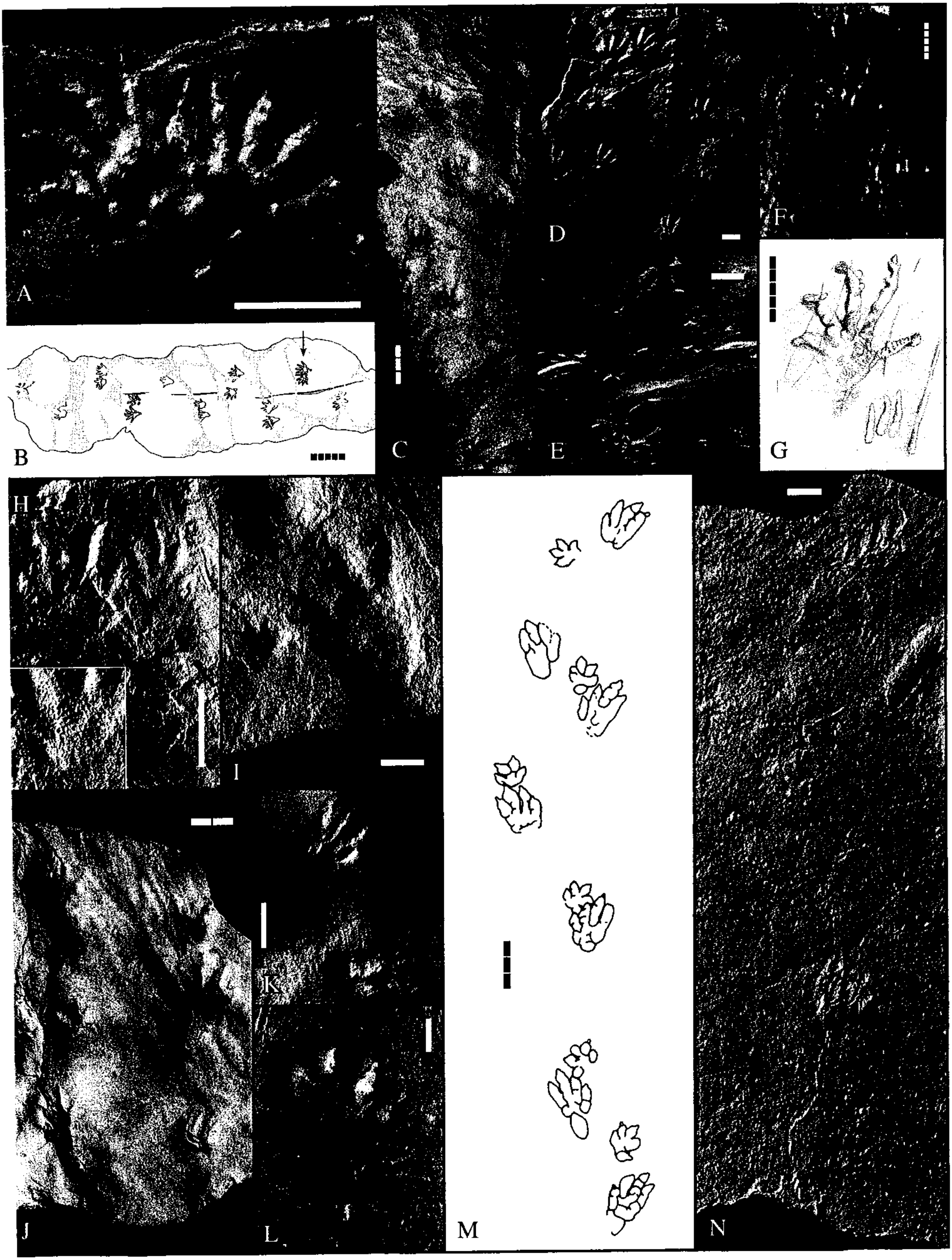
Figure 9. Quadrupedal tracks from the Riker Hill quarry. **A**, Right manus-pes set of *Ameghinichnus* n. sp. from upper unit 5, Dinosaur Park (AMNH 29298, collected by Larry Felder, 1978). Manus is on left and pes is on right. **B**, Drawing of trackway of *Ameghinichnus* n. sp. Arrow shows manus pes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

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

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

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

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

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

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

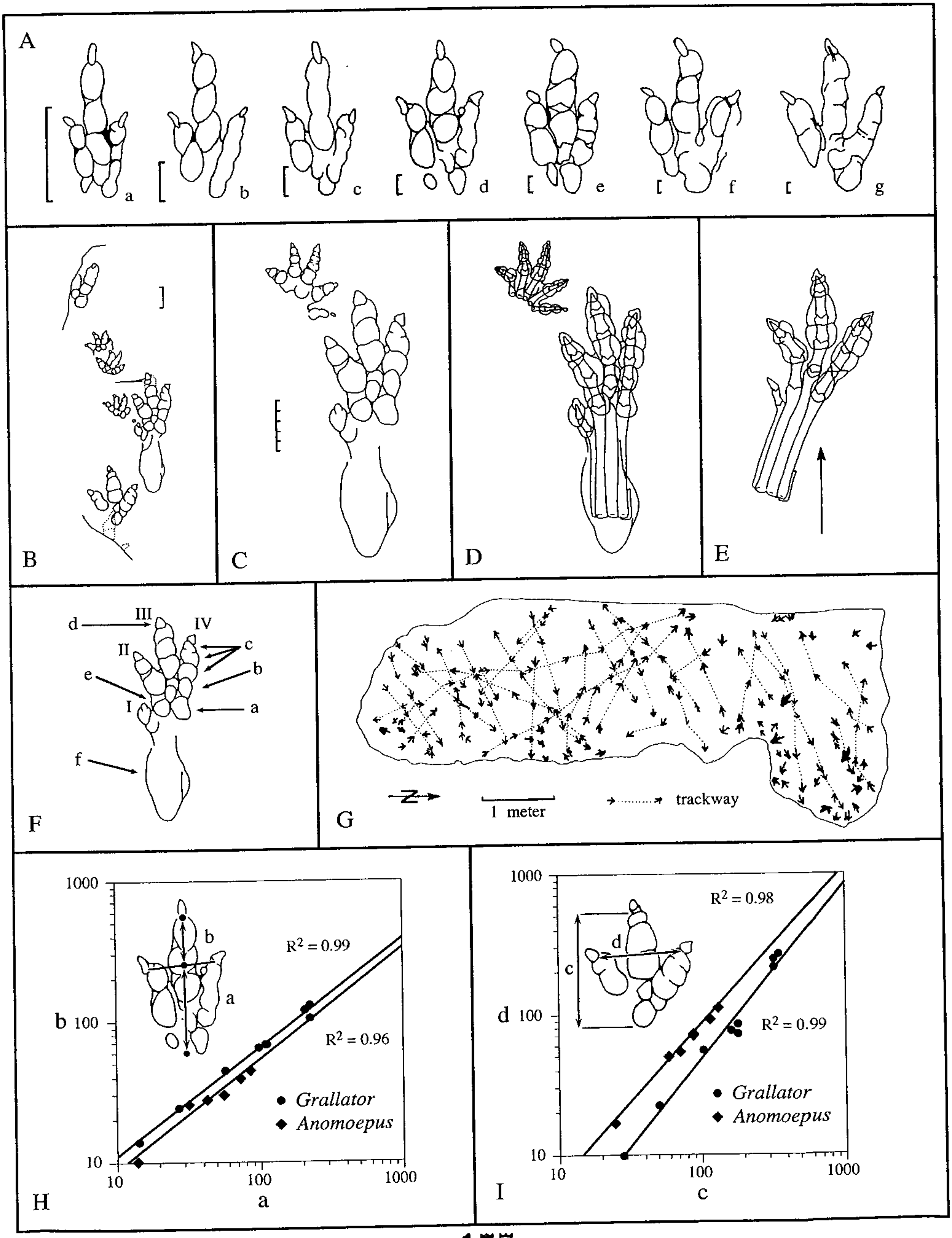
Archosauria (ruling reptiles, including birds)
Suchia (crocodiles and their extinct kin)
Crocodylomorpha (true crocodiles and nearest relatives)
Ichnogenus *Batrachopus*
Batrachopus sp.

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

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

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

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

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

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

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

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

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

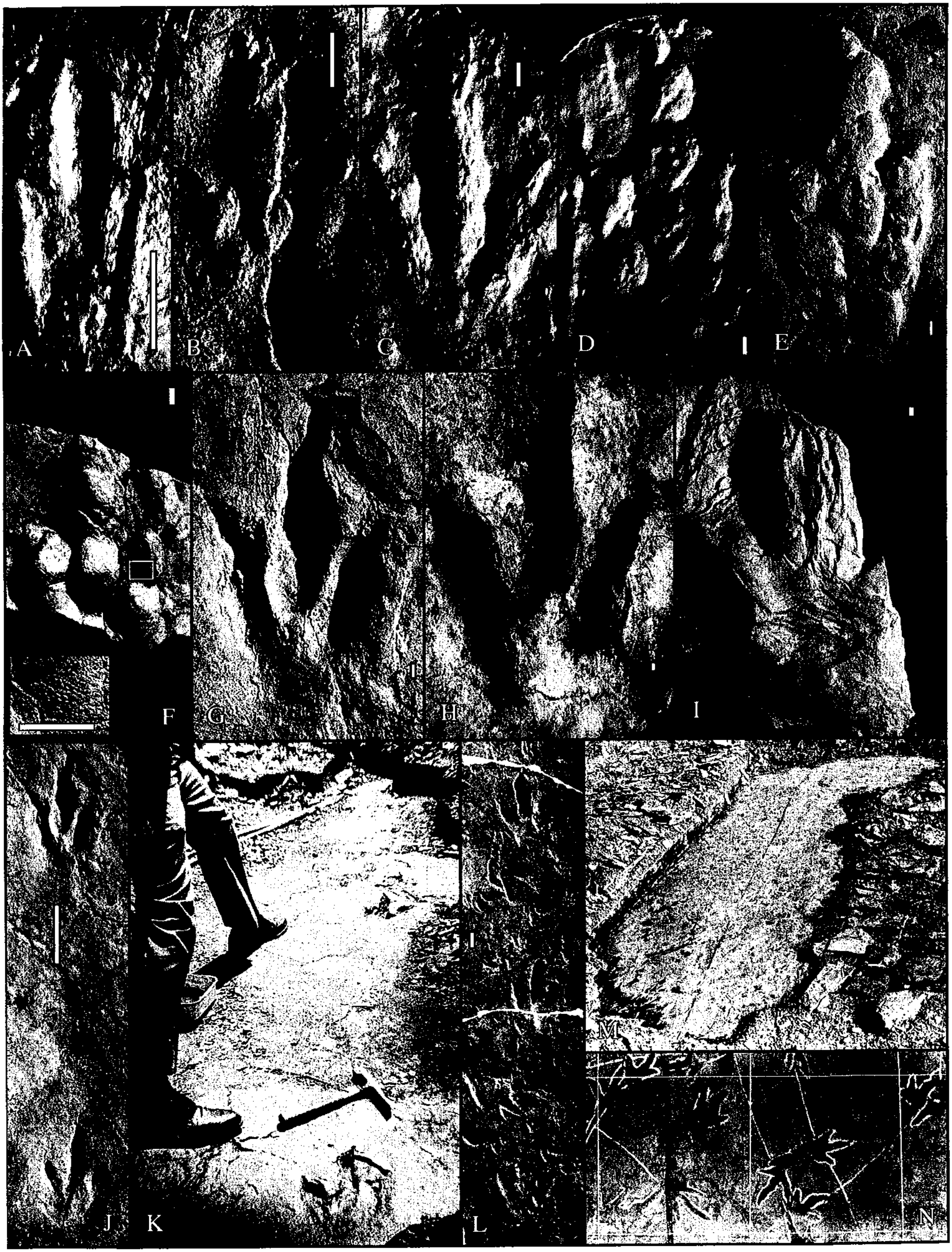
appear morphologically quite distinct. However, when we attempt to place other specimens in these taxa we find that there are a multitude of intermediate forms. This problem was apparent to Edward Hitchcock who, along with his son (C. H. Hitchcock) erected dozens of species for these intermediates which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

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

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

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

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

Theropoda (carnivorous dinosaurs) *incertae sedis*

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

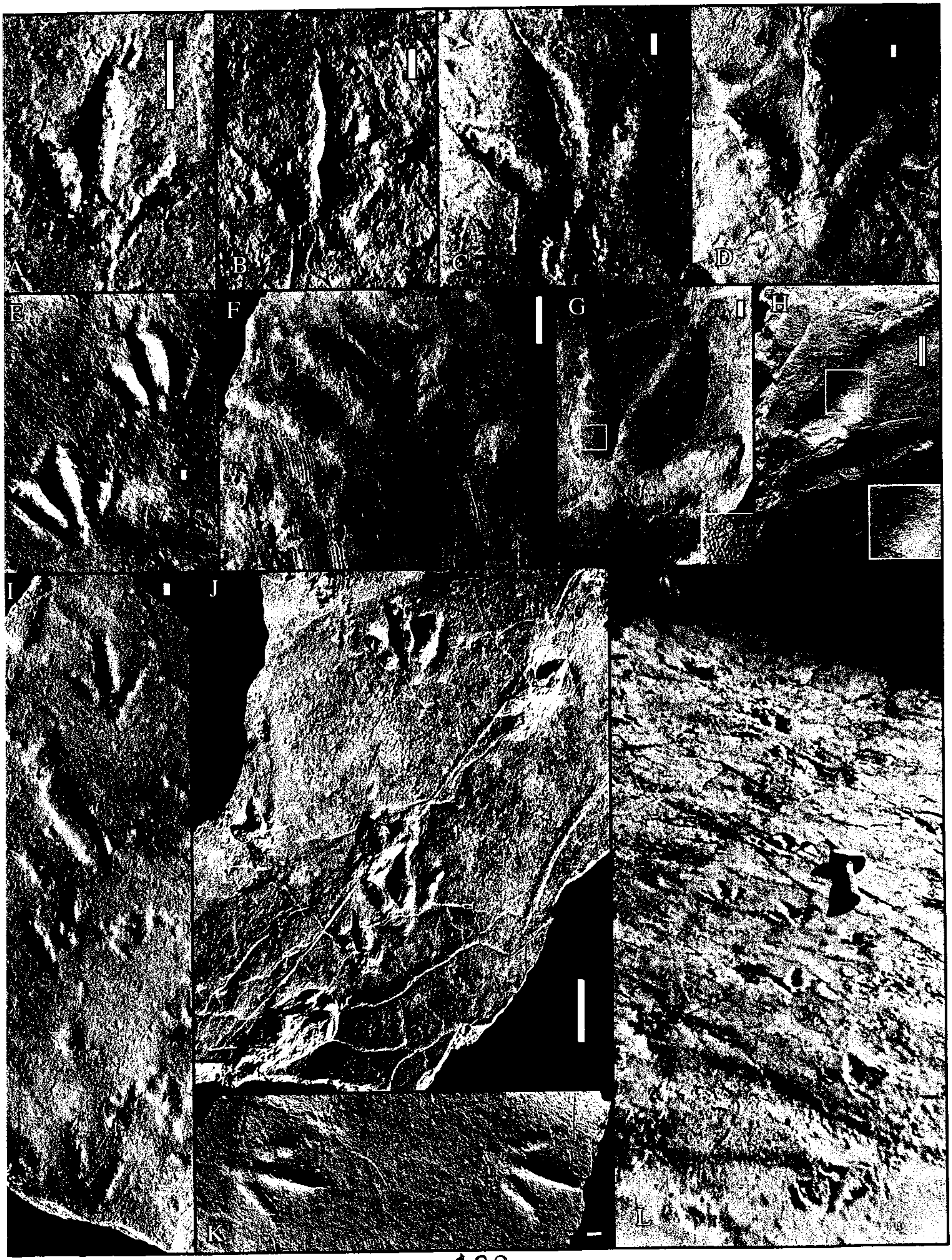
Ornithischia ("bird-hipped dinosaurs) *incertae sedis*
Ichnogenus *Anomoepus*
Anomoepus scambus

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

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

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

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

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

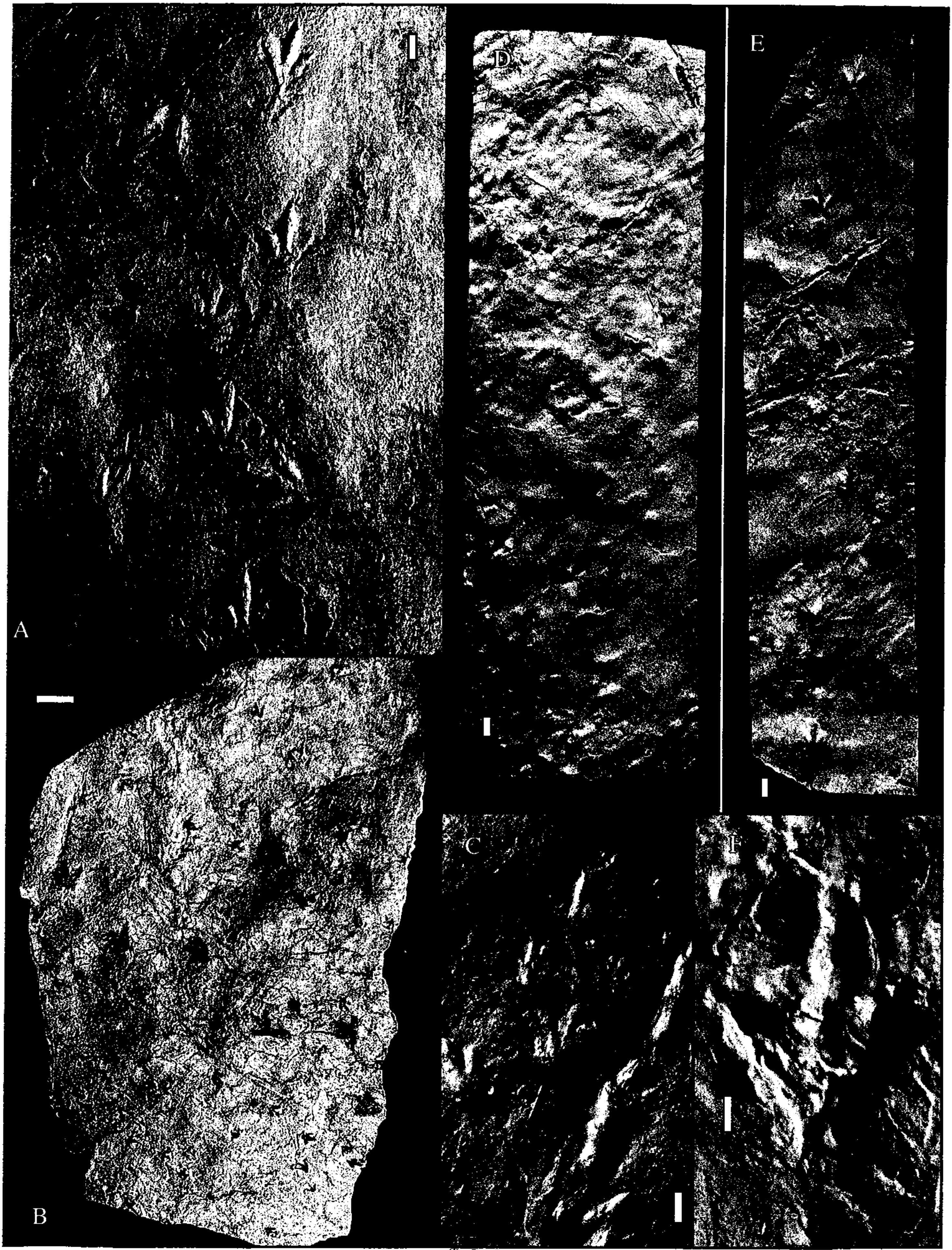
Anomoepus is characterized by a less well developed pad structure in the pes than *Grallator*. Although the skin texture (Figs. 10, 12) is very similar to *Grallator*, the pads tend to be separated by smaller narrow pads, suggesting some flexing of the foot was common. The pads on the hand show this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

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

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

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

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

PALEOENVIRONMENTS AND PALEOECOLOGY

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

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

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

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

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

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

CONCLUSIONS

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

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AN OVERVIEW OF CONODONTS FROM NEW JERSEY

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INTRODUCTION

Conodonts are the microscopic toothlike hard parts of an extinct group of marine vertebrates having affinities to the jawless fishes (e.g., hagfish). Since the first discovery of a nearly complete conodont animal from the Lower Carboniferous of Scotland (Briggs and others, 1983), several other animals have been found (Mikulic and others, 1985; Aldridge and Theron, 1993). The name conodont applies to the animal as well as its only known hard parts. These hard parts, conodont elements, generally range from 0.1 to 1 mm in length, are composed of calcium phosphate, occur in a variety of shapes, even within a single animal (like the variety of tooth shape in many other vertebrates), and formed part of a feeding apparatus. Conodonts range from the Cambrian through Triassic (an interval of ~300 million years), had worldwide distribution in most marine environments, and are one of the major groups of index fossils throughout their geologic range. An excellent summary of conodont taxonomy, biostratigraphy, and paleoecology is provided by Sweet (1988). Conodonts are also indices of thermal metamorphism (Epstein and others, 1977; Rejebian and others, 1987). The trace amount of organic matter sealed within these transparent skeletal elements visibly changes from pale yellow, to amber, light brown, dark brown, and black in the range of 50° to 300°C as a result of carbonization. Above 300°C, conodonts change from black, to gray, opaque white, and, finally, crystal clear as a result of carbon loss and recrystallization. These color changes, termed color alteration indices (CAI), have been reproduced and calibrated in the laboratory so that conodonts have become valuable geothermometers.

Previous Studies in New Jersey

Conodonts are known only from northwestern New Jersey including at least 180 collections from about 90 localities that could be plotted separately on figure 1 (Harris and others, 1995). Only a few publications describe conodonts from New Jersey. The first such report was by Ethington and others (1958) on conodonts from Middle Ordovician siltstone in the Jutland klippe sequence (fig. 1, locs. HB-6, CH-1). Subsequently, Barnett (1965) described Middle Ordovician conodonts from the Jacksonburg Limestone; all of Barnett's localities have been recollected in the course of geologic mapping (Drake and others, in press) and are included on figures 1 and 2. Barnett (1966, 1971, 1972), Epstein (1970), and Denkler and Harris (1988) reported on conodonts from uppermost Silurian and lowermost Devonian rocks in northwesternmost New Jersey, and Barnett (1966, 1971) described latest Silurian conodonts from the Green Pond Mountain area (fig. 1, loc. DO-1). Harris and others (1978) mapped conodont CAI values in Paleozoic rocks in the Appalachian basin including New Jersey, and Karklins and Repetski (1989) showed the distribution of selected Ordovician conodont faunas and their CAI values in the state. In addition, several abstracts and two undergraduate theses on Ordovician conodonts in New Jersey contain important stratigraphic and distribution data (e.g., Savoy, 1981).

In the past 20 years, conodonts have been used more than any other fossil group for correlation and to refine the age of lower Paleozoic marine rocks in New Jersey. Conodonts have been recovered chiefly from carbonate-bearing Upper Cambrian to Middle Ordovician and Upper Silurian and Lower Devonian rocks (fig. 3). Conodonts have also been identified on bedding planes of fine-grained siliciclastic rocks in the Cambrian and Ordovician Jutland klippe sequence where they are locally very abundant. Conodonts have been particularly important for correlation and geologic mapping of the Beekmantown Group, a lithologically repetitious and complexly deformed unit that generally lacks other fossils. Conodonts from New Jersey have been relatively little studied because they are mostly deformed and fractured (pl. I:A-C,H; pl. II:Y; pl. III;V,X,Z). Most of the Paleozoic rocks in which they occur have undergone very low to low grade metamorphism, are complexly deformed, cleaved, and are relatively poorly exposed.

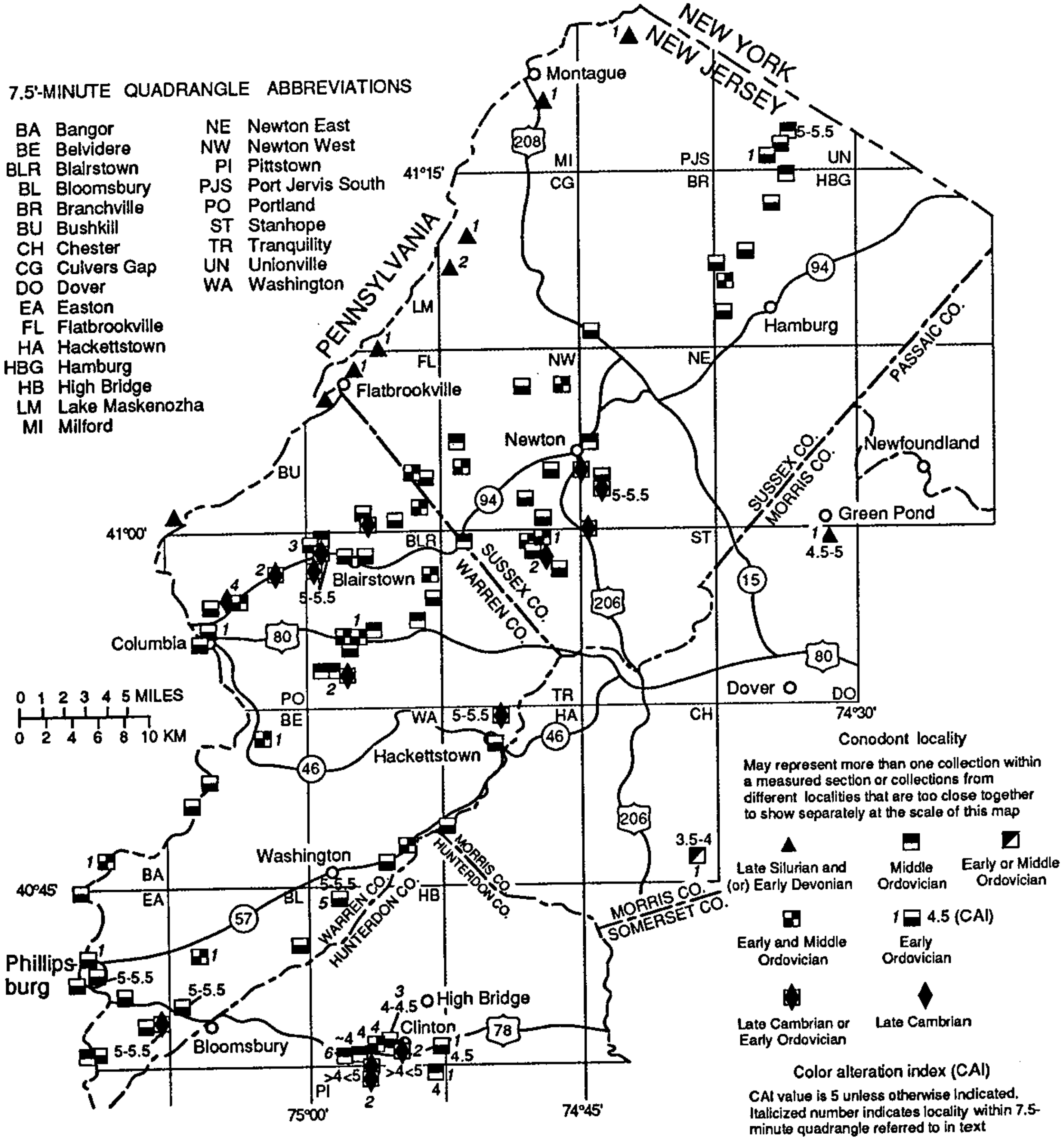

Figure 1. Index map of northwestern New Jersey showing conodont localities. See figure 2 for geologic setting.

Consequently, systematic collections from measured sections are difficult to obtain. In addition, most of the carbonate-bearing Paleozoic stratigraphic units in New Jersey, excluding the Stonehenge Formation and Jacksonburg Limestone, are poorly productive of conodonts (1-10 elements/kg). All of the above make biostratigraphic and taxonomic studies of conodonts in New Jersey a difficult as well as long-term undertaking. This report includes collections made by many geologists in the last three decades, chiefly related to geologic mapping. Foremost among these are A.A. Drake, Jr., J.B. Epstein,

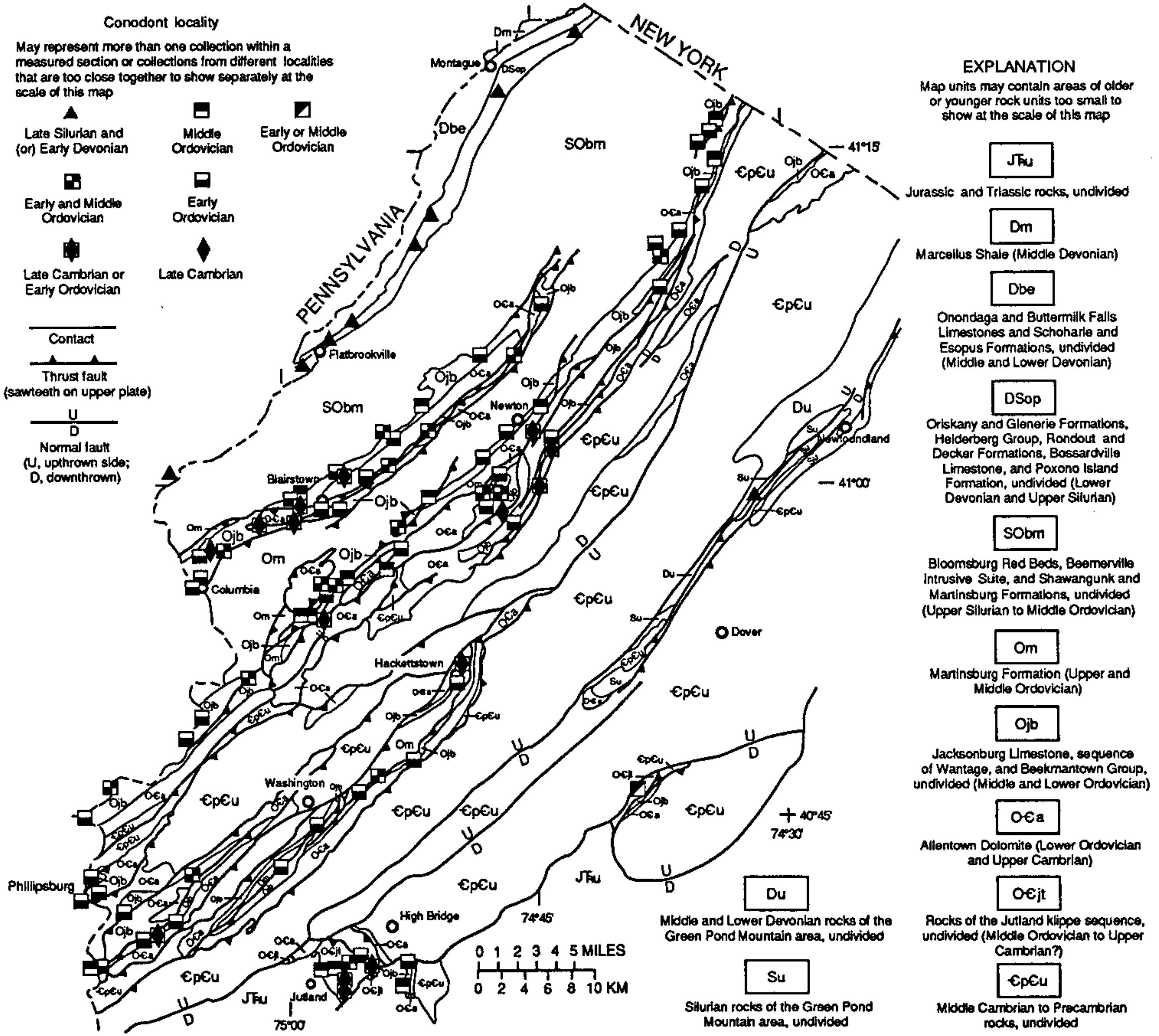

Figure 2. Generalized geologic map of northwestern New Jersey showing conodont localities (generalized from Drake and others, in press).

P.T. Lyttle, and ourselves, U.S. Geological Survey, and R. Dalton, G.C. Herman, and D.H. Monteverde, New Jersey Geological Survey.

STRATIGRAPHIC DISTRIBUTION OF CONODONTS IN NEW JERSEY

Upper Cambrian and Lower Ordovician Rocks

Allentown Dolomite (Upper Cambrian and Lower Ordovician?)

The oldest stratigraphic unit to produce conodonts in New Jersey is the Allentown Dolomite (fig. 3). A limestone within the Allentown (fig. 1, loc. TR-2) yielded a single element of *Proconodontus muelleri* (pl. I:Z), indicating a latest Cambrian age. A few other Allentown localities also have produced a very few conodonts, but all are taxa that range from the Late Cambrian into the Early Ordovician.

Beekmantown Group

Stonehenge Formation (Upper Cambrian? and Lower Ordovician, lower Ibexian)

The Stonehenge Formation has produced the largest number of Early Ordovician conodonts from the New Jersey carbonate platform succession because the Stonehenge interval was intensively examined during recent geologic mapping and its depositional setting was more favorable for conodonts than other Beekmantown Group rocks. Our use of Stonehenge Formation, as well as Rickenbach Dolomite and Epler Formation, generally follows that of Hobson's (1963) regional stratigraphic study of the Beekmantown Group in southeastern Pennsylvania, except that the Stonehenge is now recognized in New Jersey (Drake and others, in press). During deposition of the Allentown Dolomite and Beekmantown Group, much of North America, including New Jersey, was a shallow marine carbonate platform with predominantly shallow subtidal to supratidal depositional settings. Water temperature and salinity were undoubtedly elevated producing conditions unfavorable for abundant and diverse faunas. Some limestones (or dolomitized limestones) in the Stonehenge (and overlying Epler Formation) represent more "normal-marine" shallow subtidal conditions. These intervals generally produce indentifiable conodonts even though other organic remains are virtually absent. Other organisms may have once been present but their remains have not been preserved.

The lack of data near the gradational contact of the Stonehenge Formation with the underlying Allentown Dolomite, combined with the lack of agreement about the level for the Cambrian-Ordovician boundary, does not allow accurate placement of this contact; all assignable collections from the Stonehenge, however, are Ibexian (fig. 3). Collections from the earliest Ibexian *Cordylodus proavus* and *C. intermedius* Zones include both the name-bearing species as well as subzonal indicators such as *Clavohamulus elongatus* (pl. I:AF), *Hirsutodontus simplex* (pl. I:AC), and *Clavohamulus hintzei* (pl. I:AG).

Most limestones within the Stonehenge of New Jersey fall within the short interval of the *Cordylodus angulatus* Zone or the succeeding, geographically and stratigraphically extensive, *Rossodus manitouensis* Zone. Collections from limestones within the *R. manitouensis* Zone can contain diverse as well as common to abundant conodonts (~10-100 elements/kg). Besides the distinctive zonal index (pl. I:J-L), these collections usually include the tropical-cosmopolitan species *Variabiloconus bassleri* (pl. I:A-D), *"Oistodus" triangularis* (pl. I:M), and *Scolopodus sulcatus* (pl. I:H-I). Less common but important species within this zone are *Acanthodus uncinatus* (pl. I:E), *Chosonodina herfurthi* (pl. I:P), *Clavohamulus densus* (pl. I:R), *Loxodus bransoni* (pl. I:S), and *"Paltodus" spurius* (pl. I:T). The Stonehenge conodont faunas, like those in the rest of the Beekmantown Group, are shallow-water, tropical to low-temperate species associations typical of the North American Midcontinent Faunal Realm.

Rickenbach Dolomite (Lower Ordovician, lower and middle Ibexian)

The lower contact of the Rickenbach Dolomite is gradational with the Stonehenge Formation and occurs within the *R. manitouensis* Zone. Thus, it is difficult or impossible to distinguish isolated dolostone outcrops of most of the Rickenbach from much of the upper part of

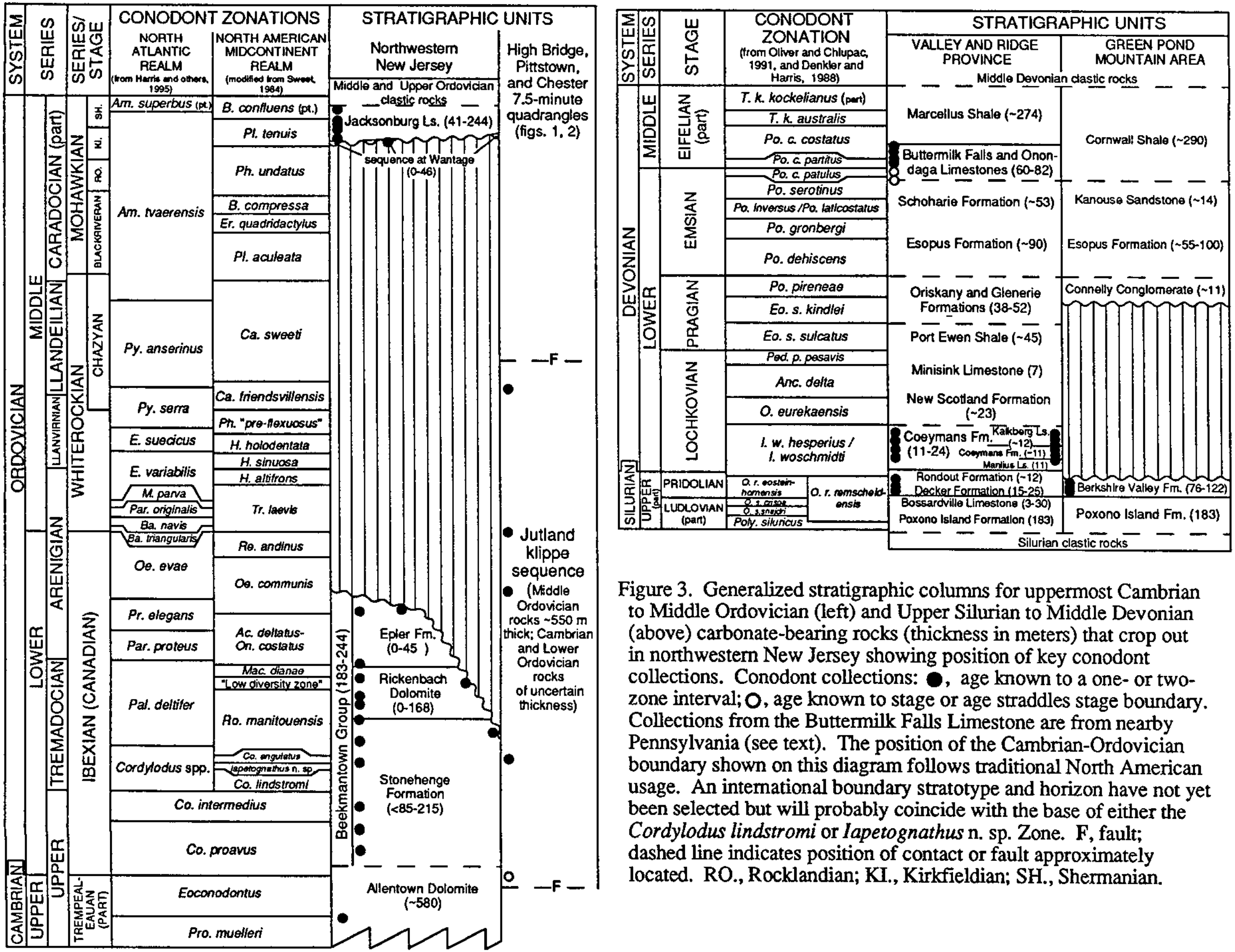

Figure 3. Generalized stratigraphic columns for uppermost Cambrian to Middle Ordovician (left) and Upper Silurian to Middle Devonian (above) carbonate-bearing rocks (thickness in meters) that crop out in northwestern New Jersey showing position of key conodont collections. Conodont collections: ●, age known to a one- or two-zone interval; ○, age known to stage or age straddles stage boundary. Collections from the Buttermilk Falls Limestone are from nearby Pennsylvania (see text). The position of the Cambrian-Ordovician boundary shown on this diagram follows traditional North American usage. An international boundary stratotype and horizon have not yet been selected but will probably coincide with the base of either the *Cordylodus lindstromi* or *Iapetognathus* n. sp. Zone. F, fault; dashed line indicates position of contact or fault approximately located. RO., Rocklandian; KI., Kirkfieldian; SH., Shermanian.

the Stonehenge either lithically or faunally. Generally, however, the dolostones of the Rickenbach represent more restricted depositional environments so that, if they yield conodonts, the faunas are less abundant and less diverse than those of the Stonehenge.

The upper part of the Rickenbach contains species of the "Low diversity zone" and the *Macerodus dianae* Zone (fig. 3). Other than rare elements of *M. dianae* (pl. II:X,Y), this relatively thin interval usually produces only rather morphologically generalized conodonts such as *Oneotodus simplex* and *Eucharodus* spp., as well as *Colaptoconus quadraplicatus* (pl. II:AG) and *Striatodontus*? *prolificus* (pl. II:AD,AE).

Epler Formation (Lower Ordovician, middle and upper Ibexian)

The Epler Formation, gradational upward from the Rickenbach Dolomite, is mostly dolostone, but does contain some limestones that help distinguish these formations. The contact is within the *M. dianae* Zone (fig. 3). Collections from limestones low in the formation may contain rather diverse faunas, but abundance is generally low. Characteristic species include *M. dianae* (pl. II:X,Y), *Protopanderodus leei* (pl. II:AB,AC), *Scolopodus floweri* (pl. II:U-W), as well as *Colaptoconus quadraplicatus* and *Eucharodus parallelus*.

Very little is known about the distribution of conodonts in the middle and upper parts of the Epler in New Jersey because these strata have not been systematically sampled. A few isolated samples containing *Diaphorodus delicatus* (pl. II:O) indicate the formation extends at least into the late Ibexian *Oepikodus communis* Zone. In addition, *O. communis* (pl. II:Q) was recovered from a redeposited cobble of Epler lithology within the Jacksonburg Limestone in an area from which the Epler was eroded (Savoy, 1981).

Middle Ordovician

Jacksonburg Limestone (late Middle Ordovician)

The Jacksonburg Limestone disconformably overlies all of the Beekmantown Group formations in northwestern New Jersey, as these rocks were exposed and eroded during the early Middle Ordovician. Savoy (1981) documented the presence of conodonts ranging in age from early to late Ibexian (to perhaps early Whiterockian) in carbonate cobbles incorporated within the basal and lower Jacksonburg. In addition, isolated exposures of dolomitic to shaly carbonate rocks lie immediately beneath the Jacksonburg in some areas. These rocks, mapped and termed the sequence at Wantage by Monteverde and Herman (1989) and Drake and others (in press), probably are remnants of a unit that filled topographic lows on the eroded Beekmantown surface during initial late Middle Ordovician transgression. Some samples from this unit have produced *Phragmodus undatus* among other species. This species and the position of the sequence at Wantage beneath the Jacksonburg indicate a Rocklandian or Kirkfieldian age.

The limestones of the Jacksonburg generally contain abundant and diverse shelly fossils and probably formed in normal-marine subtidal conditions. These limestones also produce the largest conodont yields of all New Jersey carbonate rocks. Most Jacksonburg samples contain the North American Midcontinent Faunal Realm species *Phragmodus undatus* (pl. III:V-Z), *Plectodina tenuis* (pl. III:R,S), *Aphelognathus politus* (pl. III:M-Q), as well as pandemic species such as *Panderodus gracilis* and *Drepanoistodus suberectus* (pl. III:AC). All these species are rather long-ranging, but some constrain the lower limit of the formation to an age no older than late Middle Ordovician (Kirkfieldian Stage) *Plectodina tenuis* Zone (fig. 3). As noted by Barnett (1965), at some localities the Jacksonburg faunas include species characteristic of the North Atlantic Faunal Realm together with North American Midcontinent species. This probably indicates a more offshore, open-marine setting for these more eastern localities (e.g., fig. 2, loc. PI-1). North Atlantic Realm species found in the Jacksonburg include *Icriodella superba* (pl. III:A-D), *Rhodesognathus elegans* (pl. III:L), and *Amorphognathus superbus* (pl. III:F,G). The presence of *A. superbus* is significant because it ties the Jacksonburg into the cosmopolitan North Atlantic zonation (fig. 3). The age of the upper part of the Jacksonburg is not well constrained; graptolites in the lower part of the overlying Martinsburg Formation indicate an age no younger than early Edenian (Drake and others, in press).

Jutland klippe sequence

Very different conodont faunas occur sporadically in the mostly siliciclastic rocks of the Taconic-type klippen near Clinton (Jutland klippe) and near Chester (Peapack klippe, but included in the Jutland klippe sequence), New Jersey (figs. 2, 3). All faunas, both conodont and graptolite, known from these areas, as well as the sedimentology, point to deposition in continental slope to oceanic basin environments (see also Drake, 1969; Perissoratis and others, 1979). All conodonts known from the klippe sequence thus far are cosmopolitan North Atlantic Realm or pandemic species.

Conodonts are locally abundant on bedding surfaces of siltstone and fine-grained sandstone in the Jutland klippe sequence. These include mostly elements of *Periodon aculeatus* (pls. II:F, III:AB) and a few other long-ranging taxa that give an overall age of early to middle Middle Ordovician. However, two specimens of *Pygodus*, a biostratigraphically important genus, known from the sequence (Ethington and others, 1958, and this report, pl. III:AA), restrict the age to the Llanvirnian and (or) Llandeilian. Some new collections made by D.C. Parris (N.J. State Museum), from a lower stratigraphic level contain Early Ordovician graptolites and abundant conodont elements of *Paracordylodus gracilis* (fig. 1, loc. HB-3). These conodonts are best assigned an early or early middle Arenigian (early late Ibexian) age.

Some collections of calcareous rocks from the Jutland klippe sequence have yielded older conodonts. The oldest faunas span the Cambrian-Ordovician boundary (fig. 3), and include *Eoconodontus notchpeakensis* (pl. I:X), and species of the protoconodont *Phakelodus* (pl. I:V). Somewhat younger samples contain species of the cosmopolitan genus *Cordylodus* and are assignable to the lower Ibexian or lower Tremadocian (pl. II:G,H). A calcareous sample from the Peapack klippe (fig. 1, loc. CH-1) contains abundant *Periodon flabellum* (pl. II:A-E) and other species (pl. II:I-M), and is of latest Early or earliest Middle Ordovician age.

Upper Silurian and Lower Devonian Rocks

Valley and Ridge province

Decker Formation (Upper Silurian, upper Pridolian)

The Decker Formation is the oldest Silurian unit to produce conodonts (fig. 3). No conodonts have been recovered from the underlying Bossardville Limestone in New Jersey and samples from Pennsylvania have produced only indeterminate conodont fragments (Denkler, 1984). The Poxono Island Formation underlies the Bossardville and contains some carbonate beds, but it has not produced conodonts either in New Jersey or nearby Pennsylvania (Denkler, 1984 and A.G. Harris, unpublished data). Barnett (1971) showed the distribution of conodonts in samples from the Decker Formation at loc. PJS-1 (fig. 1). Barnett's data indicate conodonts are common (11 elements/kg) but diversity is low; *Ozarkodina remscheidensis* makes up more than 98% of the fauna and *Oulodus elegans* is the only other conodont on the basis of our multielement analysis of Barnett's form-element taxonomy. These two species also occur in the Decker in Pennsylvania (Denkler and Harris, 1988). The Decker contains a relatively diverse macrofauna including brachiopods, corals, mollusks, and pelmatozoans. Fossils and sedimentary structures indicate a high-energy, shoal-water depositional setting. The low diversity of conodonts suggests normal-marine conditions were intermittent or that physical and chemical barriers elsewhere in the Appalachian basin kept less eurytopic conodont species from reaching New Jersey.

Oulodus elegans indicates the Decker Formation is no older than late Ludlovian and no younger than latest Pridolian. Regional stratigraphic relationships indicate the Decker is late Pridolian.

Rondout Formation (Upper Silurian and Lower Devonian, upper Pridolian and lower Lochkovian)

The Rondout Formation consists of laminated, mud-cracked, argillaceous carbonate mudstone and dolostone containing one widespread, thin biostromal bed. The Rondout formed in a restricted lagoon setting (Epstein and others, 1967). Only one sample (fig. 1, loc. PJS-1) from the lower part of the formation in New Jersey produced conodonts (Barnett, 1971). Abundance and species composition is the same as in the Decker. *Oulodus elegans* restricts the lower part of the Rondout to the Late Silurian. The Silurian-Devonian boundary was placed in the middle of the Rondout Formation on the basis of sequence stratigraphy and regional conodont biostratigraphy and biofacies by Denkler and Harris (1988). Earlier, Barnett (1972) positioned this boundary at the base of the overlying Manlius Limestone in New Jersey using comparative morphometric analysis of Pa elements of *Ozarkodina remscheidensis* from New Jersey, Nevada, and Czechoslovakia. We believe changes in the shape of Pa elements of *O. remscheidensis*, a long-ranging and variable species, reflect recurrent environmental responses, are not evolutionary, and should not be used for long-distance correlation.

Manlius Limestone (Lower Devonian, *I. woschmidti* Zone, lower Lochkovian)

Conodonts are common (~10 elements/kg) in the Manlius Limestone in New Jersey (Barnett, 1966; Epstein, 1970; A.G. Harris, U.S. Geological Survey collections) and only slightly more diverse than in underlying Silurian rocks. *Ozarkodina remscheidensis* (pl. IV:E, G-I) continues to make up at least 98% of the collections indicating intermittently restricted conditions. *Oulodus cristagalli* and *Belodella devonica* are rare. One specimen of *Icriodus woschmidti*, an auxiliary guide to the base of the Devonian, was found 2.6 m below the top of the formation at loc. PJS-1 (Denkler and Harris, 1988) confirming the Devonian age based on regional relationships. Southwest of Montague, N.J., beds correlative to the Manlius become increasingly quartzose and are included in the more heterogeneous Coeymans Formation (fig. 3; Epstein and others, 1967).

Coeymans Formation (Lower Devonian, *I. woschmidti* Zone, lower Lochkovian)

The Coeymans Formation yields more abundant (~20 elements/kg) and possibly more diverse conodonts than any other uppermost Silurian or lowermost Devonian unit in New Jersey (Barnett, 1966, 1971; Epstein, 1970). The Coeymans includes bioclastic grainstone, packstone, and lesser wackestone that contain varying amounts of quartz silt and sand as well as biorudite and calcareous quartz-pebble conglomerate. The biorudites produce fewer conodonts than other facies in the formation. The conodont fauna of the Coeymans (using data in Barnett, 1966, and Epstein, 1970) consists of *Ozarkodina remscheidensis* (76%) (pl. IV:A-D, F), *Icriodus woschmidti* (12%) (pl. IV:Q-V), *Oulodus cristagalli* (9%) (pl. IV:K-O), *Belodella devonica* (2%) (pl. IV:P), *Pseudooneotodus beckmanni* (~1%) (pl. IV:J), and 1 specimen of *Panderodus unicostatus* (Branson and Mehl). Sedimentary structures and fossils indicate the Coeymans formed in a high- to moderate-energy depositional setting accounting for the increase in icriodids and oulodids.

Kalkberg Limestone (Lower Devonian, *I. woschmidti* Zone, lower Lochkovian)

The Kalkberg Limestone extends into New Jersey only as far southwest as the Lake Maskenozha quadrangle (fig. 3; Epstein and others, 1967). The Kalkberg is like the underlying Coeymans Formation, but is more argillaceous and contains more chert. Nevertheless, the Kalkberg produces nearly the same conodont species in the same order of abundance as the Coeymans (Epstein, 1970). The presence of *Icriodus woschmidti* restricts the formation to the earliest Lochkovian. The Kalkberg was deposited seaward of the Coeymans in slightly deeper water.

Post-Kalkberg Limestone Devonian rocks

No conodonts have been reported from Devonian rock units younger that the Kalkberg Limestone in northwestern New Jersey. Of these units (fig. 3), the Glenerie Formation and Buttermilk Falls Limestone have the best potential for conodonts. Common to abundant conodonts have been recovered from measured sections of the Buttermilk Falls in its type area near East Stroudsburg, Pa. (~lat. 41°00', long. 75°08'-11') (A.G. Harris, written communication, 1982, to J.B. Epstein; U.S. Geological Survey collections 10635-SD to 10642-SD). The conodonts indicate the lower one-third of the formation is no older than the *serotinus* Zone and the remainder of the formation represents the *partitus* and *costatus* Zones. In the type area, the Tioga Ash Bed is 9 m below the top of the Buttermilk Falls Limestone. The Tioga is known to lie within the *costatus* Zone at many localities in the Appalachian basin (e.g., Klapper and Johnson, 1980).

Green Pond Mountain area

A narrow belt of Paleozoic rocks lies within the New Jersey Highlands, east of the Valley and Ridge province (fig. 2). Barnett (1966, 1971) described conodonts from carbonate-bearing uppermost Silurian and lowermost Devonian rocks at one locality in the Green Pond Mountain area of New Jersey (fig. 1, loc. DO-1). Three large samples from fossiliferous limestone beds in the Berkshire Valley Formation produced only *Ozarkodina remscheidensis* in low numbers (4 /kg). On the basis of regional stratigraphic relations, Barnett (1966, 1971) considered the Berkshire Valley correlative to the Decker and Rondout Formations of the Valley and Ridge province.

CONODONT COLOR AND TEXTURAL ALTERATION

Most conodonts from New Jersey have CAI values of 5 and, more rarely, higher (fig. 1) indicating they reached at least 300°C and burial depths of at least 10 km. Values of 4.5 to as low as 3.5-4 are limited to the High Bridge, Pittstown, and Chester 7.5-minute quadrangles (fig. 1), chiefly in the Jutland klippe sequence although conodonts from the Beekmantown Group and Jacksonburg Limestone in the same area have similarly low CAI values (fig. 1, locs. PI-1 and HB-1-3 and fig. 2). The data suggest that all these rocks lie structurally above and were never as deeply buried as nearby parautochthonous correlative strata with CAI values of 5 and 5-5.5 (e.g., fig. 1, loc. HB-5) as well as considerably younger Upper Silurian and Lower Devonian rocks with CAI values of 5 at least 40 km to the northwest.

Most conodonts from New Jersey are poorly preserved texturally, particularly specimens from dolostones in which saline pore waters probably promoted surface corrosion and recrystallization of conodonts during diagenesis. In limestones, recrystallization of conodonts generally begins at CAI 5. Because even the youngest conodonts from New Jersey have CAI values of 5, they too show varying degrees of recrystallization depending on the texture and composition of their host rock (see pls. I-IV). Conodonts from porous rocks such as grainstones may be more recrystallized than those from more poorly sorted rocks. For example, the specimen shown in plate IV:A is from a wackestone and is less recrystallized than the specimen shown in plate IV:K from a grainstone/packstone. At the temperatures associated with CAI values of 5 or higher, carbonate grains may anneal to the surface of conodonts. When such conodonts are freed from limestone by dissolving the rock in a weak acid solution, the conodonts often bear the imprint of annealed carbonate grains on their surface (e.g., pls. I:P, IV:R) even though these grains have dissolved. Conodonts extracted from dolomitic limestone, such as the Epler Formation, or quartzose carbonate rocks, such as the Coeymans Formation, generally retain the insoluble dolomite rhombs (e.g., pl. II:P,AH) or quartz grains on their surface (e.g., pl. IV:C, T).

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PLATE I

Late Cambrian and Early Ordovician conodonts from northwestern New Jersey

[Specimens on all plates are scanning electron photomicrographs and specimens are reposited in the U.S. National Museum of Natural History (USNM), Washington, D.C.; all figures X 80, unless specified otherwise; all specimens are shown in lateral view unless noted otherwise; localities shown on figure 1]

A-D. *Variabiloconus bassleri* (Furnish). A-C: tectonically deformed elements; from Stonehenge Fm. at loc. TR-1, USGS colln. 9269-CO, USNM 486915-17. D: non-deformed element from dolostone cobble in Jacksonburg Ls. (see text) at loc. BLR-1, USGS 9343-CO, X120, USNM 486918.

E. *Acanthodus uncinatus* Furnish. Stonehenge Fm. near loc. PO-1, USGS 10825-CO, USNM 486919.

F, N. "*Acanthodus*" *lineatus* (Furnish). Tall-based element (F), from uppermost Stonehenge Formation or lower part of the Rickenbach Dolomite, loc. TR-1, USGS 9380-CO, and short-based element (N), from Stonehenge Formation, loc. PO-1, USGS 10825-CO, USNM 486920, 21.

G. *Rossodus*? n. sp. Posterolateral view of coniform element; Stonehenge Formation same loc. as fig. N, USNM 486922.

H, I. *Scolopodus sulcatus* Furnish. H: deformed element from Stonehenge Fm., same loc. as figs. A-C. I: non-deformed element from cobble in base of Jacksonburg Ls., loc. BLR-2, USGS 9350-CO, USNM 486923, 24.

J-L. *Rossodus manitouensis* Repetski & Ethington. J: posterolateral view of deformed coniform element from loc. TR-1; K, L: posterolateral and inner lateral views of non-deformed coniform and oistodontiform elements from loc. PO-1. All from Stonehenge Fm., USNM 486925-27.

M. "*Oistodus*" *triangularis* Furnish. From cobble in base of Jacksonburg Limestone at loc. BLR-2, USGS 9351-CO, USNM 486928.

O. "*Drepanodus*" *pseudoconcavus* Repetski. From Stonehenge Fm. at loc. PO-1, USNM 486929.

P. *Chosonodina herfurthi* Müller. Posterior view; Stonehenge Formation or Rickenbach Dolomite at loc. UN-1, USGS 10521-CO, USNM 486930.

Q. *Clavohamulus*? n. sp. A. Postero-basal view; from Stonehenge Formation or Rickenbach Dolomite at loc. EA-1, USGS 10263-CO, USNM 486931.

R. *Clavohamulus densus* Furnish. Posterior view; Stonehenge Formation at loc. TR-1, USNM 486932.

S. *Loxodus bransoni* Furnish. From Stonehenge Fm. at loc. HB-3, USGS 10397-CO, USNM 486933.

T. "*Paltodus*" *spurius* Ethington & Clark. From Stonehenge Formation at loc. TR-1, USGS 9565-CO, USNM 486934.

U. *Aloxoconus iowensis* (Furnish). From cobble in base of Jacksonburg Limestone at loc. BLR-2, USGS 9351-CO, USNM 486935.

V. *Phakelodus* cf. *P. elongatus* An. Nearly complete fused cluster of grasping apparatus of protoconodont; from limestone bed in Jutland klippe sequence at loc. PI-2, USGS 11244-CO, X160, USNM 486936.

W. *Teridontus nakamurai* (Nogami). From cobble in base of Jacksonburg Limestone at loc. BLR-1, USGS 9333-CO, X160, USNM 486937.

X, Y. *Eoconodontus notchpeakensis* (Miller). X: rounded element from limestone bed in Jutland klippe sequence at loc. PI-2, USGS 11243-CO, Y: compressed element, from cobble in base of Jacksonburg Limestone at loc. BLR-2, USGS 9359-CO; both X120, USNM 486938, 39.

Z. *Proconodontus muelleri* Miller. From limestone within Allentown Dolomite at loc. TR-2, USGS 11242-CO, X125, USNM 486940.

AA. *Hirsutodontus hirsutus* Miller. Limestone in lower part of Stonehenge Formation at loc. PO-2, USGS 10824-CO, X125, USNM 486941.

AB. *Cordylodus angulatus* Pander. Stonehenge Fm. at loc. HB-3, USGS 10397-CO, USNM 486942.

AC. *Hirsutodontus simplex* Miller. Same loc. as fig. AA, X125, USNM 486943.

AD. *Hirsutodontus rarus* Miller. Basal margin of element slightly stretched tectonically. Same loc. as fig. AA, X120, USNM 486944.

AE. *Cordylodus proavus* Müller. Cusp of element broken, displaced posteriorly, and annealed during deformation and diagenesis. From cobble in base of Jacksonburg Limestone at loc. BLR-1, USGS 9333-CO, X160, USNM 486945.

AF. *Clavohamulus elongatus* Miller. Posterolateral view of advanced morphotype. Same loc. as fig. AA, X120, USNM 486946.

AG. *Clavohamulus hintzei* Miller. Posterior view of very slightly deformed element. Same loc. as fig. AA, X120, USNM 486947.

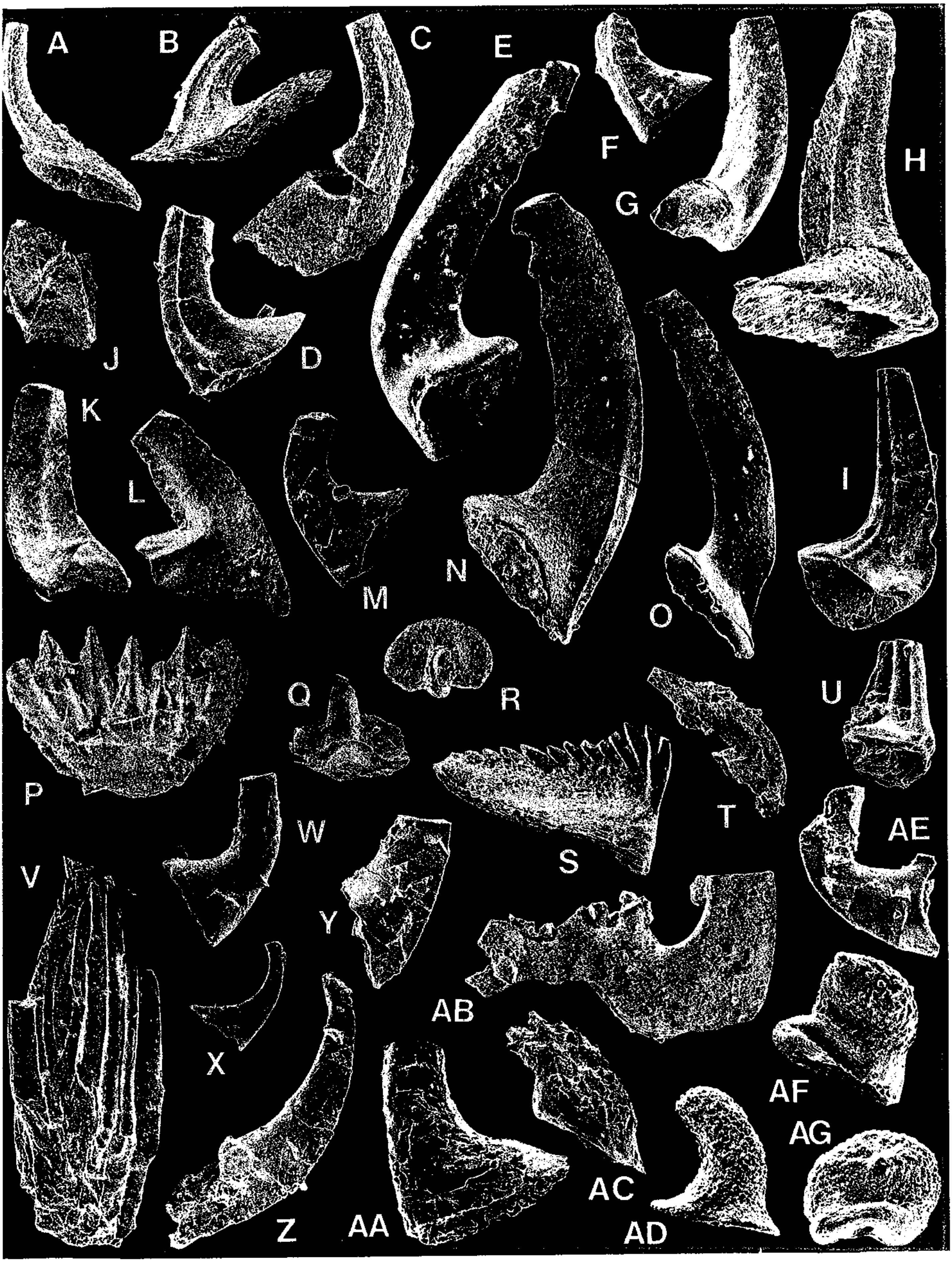
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PLATE II

Early and Middle Ordovician conodonts from northwestern New Jersey

A-E. *Periodon flabellum* (Lindström). Pa, Sb, Pb, Sc, and M elements; from a limestone in the Jutland klippe sequence at loc. CH-1, USGS 9105-CO, USNM 486948-52.

F. *Periodon aculeatus* Hadding (right) and two other ramiform conodont elements on bedding surface of siltstone from Jutland klippe, loc. HB-6, USGS 11250-CO, X50, USNM 486953.

G. *Cordylodus intermedius* Furnish. This species is an index for the lower Ibexian. From a limestone in the Jutland klippe sequence at loc. HB-4, USGS 11252-CO, USNM 486954.

H. *Cordylodus lindstromi* Druce & Jones. This is a key index species in the lower Ibexian. Same loc. as fig. G, USNM 486955.

I,J. *Protoprioniodus* sp. Oistodontiform (M) and "elongatiform" elements. Same loc. as figs. A-E, USNM 486956, 57.

K,L. *Paroistodus parallelus* (Pander). Oistodontiform and drepanodontiform elements. Same loc. as figs. A-E, USNM 486958, 59.

M. *Protopanderodus* cf. *P. rectus* (Lindström). Same loc. as figs. A-E, USNM 486960.

N. *Oneotodus costatus* Ethington & Brand. Posterolateral view of poorly preserved element. From Epler Formation at loc. BLR-3, USGS 9442-CO, USNM 486961.

O. *Diaphorodus delicatus* (Branson & Mehl). Sc element. Species is an auxiliary guide for the *Oepikodus communis* Zone in warm, restricted, shallow-water facies. Epler Formation, same loc. as fig. N, USNM 486962.

P. *Tropodus comptus* (Branson & Mehl). Specimen shows traces of annealed dolomite rhombs. Epler Formation, same loc. as fig. N, USNM 486963.

Q. *Oepikodus communis* (Ethington & Clark). Ramiform (S) element. From cobble in base of Jacksonburg Limestone at loc. BLR-1, X160, USNM 486964.

R. *Protoprioniodus aranda* Cooper. Anterolateral view. Epler Formation, same loc. as fig. N, USNM 486965.

S. "*Scolopodus*" *emarginatus* Barnes & Tuke. Posterolateral view. Epler Formation, same loc. as fig. N, USNM 486966.

T. *Chionoconus avangna* Smith. Epler Formation, same loc. as fig. N, USNM 486967.

U-W. *Scolopodus floweri* Repetski. Scandodontiform (V) and two multicostate elements. Species is an index in the middle Ibexian. Limestone in the Epler Formation, loc. BE-1, USGS 9637-CO, USNM 486968-70.

X,Y. *Macerodus dianae* Fåhraeus & Nowlan. A key species in the middle Ibexian. Element Y stretched and broken. Epler Formation, same loc. as figs. U-W, X120, USNM 486971,72.

Z,AA. *Clavohamulus*? new species B. Anterior and posterior views. Epler Formation, same loc. as figs. U-W, X160, USNM 486973,74.

AB,AC. *Protopanderodus leei* Repetski. Posterolateral views of symmetrical (AB) and asymmetrical (AC) elements. Fig. AB from Epler Formation at loc. BE-1, USGS 9637-CO; fig. AC from loc. BA-1, Epler Formation on Pennsylvania side of Delaware River; both X120, USNM 486975, 76.

AD,AE. *Striatodontus*? *prolificus* Ji & Barnes. Posterolateral (AD) and posterior (AE) views. Epler Formation, same loc. as figs. U-W, USNM 486977, 78.

AF. *Parapanderodus striatus* (Graves & Ellison). Upper view, showing cross-section of cusp. Epler Formation, same loc. as fig. AC, X240, USNM 486979.

AG. *Colaptoconus quadraplicatus* (Branson & Mehl). This is one of the most common species in the upper Ibexian rocks of the North American Midcontinent Faunal Realm. Epler Formation, same loc. as fig. N, USNM 486980.

AH. *Rossodus*? n. sp. Posterior view of coniform element. From redeposited cobble of Epler Formation or Rickenbach Dolomite lithology, in Jacksonburg Limestone at loc. BLR-1, USGS 9340-CO, X160, USNM 486981.

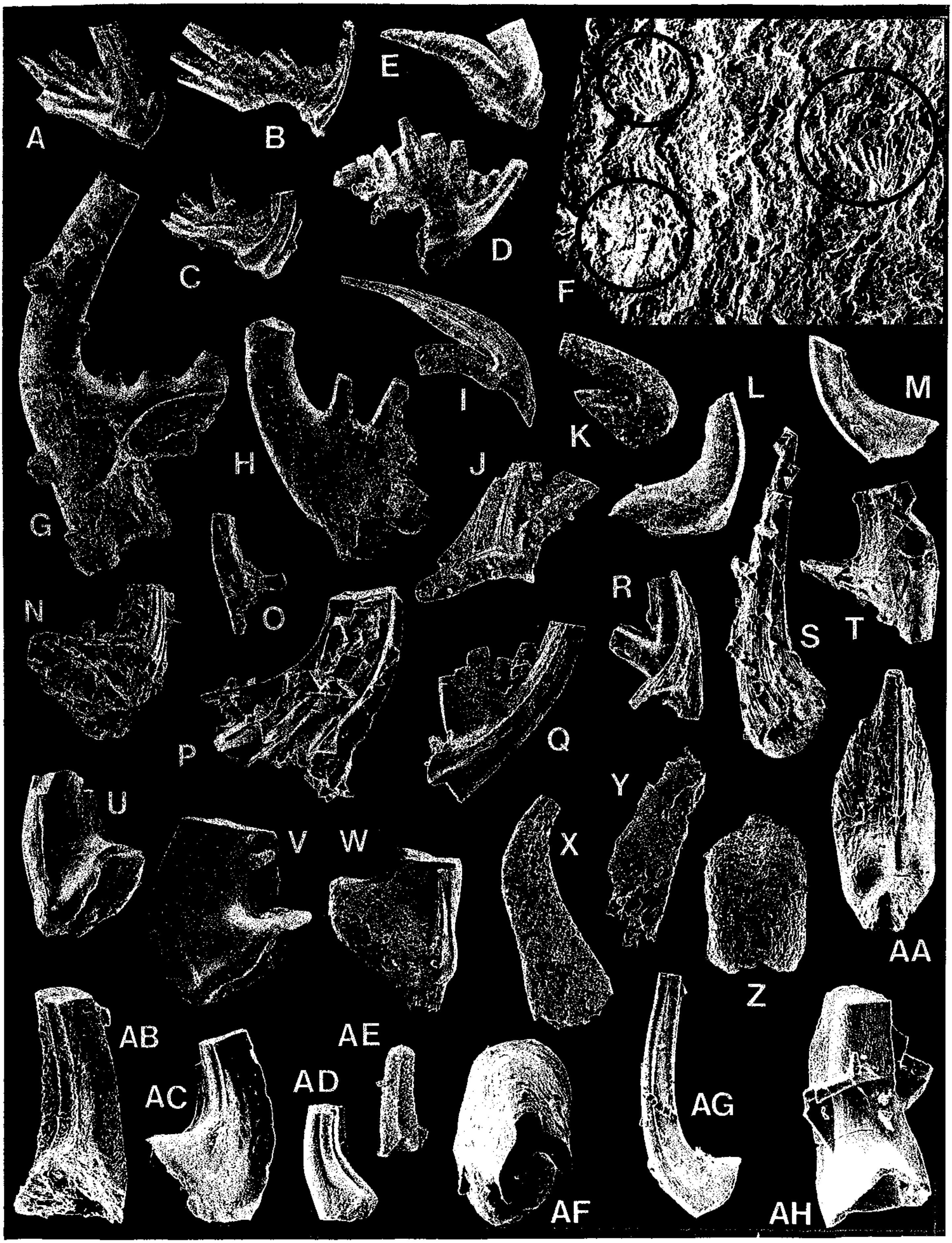
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PLATE III

Middle Ordovician conodonts from northwestern New Jersey and immediately adjacent New York [All specimens from Jacksonburg Limestone or correlative Balmville Limestone (nearby in New York), except figs. H, AA, and AB.]

A-D. *Icriodella superba* Rhodes. Pa (lateral and upper views), Sa (posterolateral view), and Pb elements, respectively. Loc. PI-1, USGS 11251-CO, USNM 486982-85.

E. *Polyplacognathus ramosus* Stauffer. Upper view of Pa element. Lower part of Balmville Limestone, at loc. 3B of Savoy, (1981), at approx. 4 mi. E of SE corner of Unionville quadrangle, in adjacent New York, USGS 9386-CO, USNM 486986.

F-H. *Amorphognathus superbus* (Rhodes). Pb (holodontiform) elements. F and G from Jacksonburg Limestone at same loc. as figs. A-D (= loc. 6 of Barnett, 1965); H, for comparison, from Upper Ordovician Kope Formation, northern Kentucky, USGS 8538-CO, USNM 486987-89.

I. *Paroistodus*? *venustus* (Stauffer). Oistodontiform element, from basal meter of Balmville Limestone at loc. 2 of Savoy (1981), Goshen quadrangle, NY, USGS 9390-CO, X120, USNM 486990.

J, K. Ramiform elements (Sd and Sa) of either *Amorphognathus superbus* or *Rhodesognathus elegans*. Jacksonburg Limestone, same loc. as figs. A-D, USNM 486991, 92.

L. *Rhodesognathus elegans* (Rhodes). P element. Same loc. as figs. A-D, USNM 486993.

M-Q. *Aphelognathus politus* (Hinde). Pa, and posterolateral views of Sb, Pb, M, and Sa elements, respectively; figs. M, P, Q from Jacksonburg Limestone above basal cobble-bearing beds at loc. BLR-1; figs. N and O from lower part of Balmville Limestone at same loc. as fig. E (loc. 3B of Savoy, 1981), USGS 9384-CO and 9385-CO, USNM 486994, 98.

R, S. *Plectodina tenuis* (Branson & Mehl). Pa and posterolateral view of Sb element. Same loc. as figs. A-D, USNM 486999, 487000.

T, U. *Plectodina*? sp. Pb (X120) and Pa elements; lower part of Balmville Limestone, same loc. as fig. E, USNM 487001, 02.

V-Z. *Phragmodus undatus* Branson & Mehl. P (figs. V-X) and S (figs. Y, Z) elements from deformed (V, X, Z) and non-deformed (W, Y) strata. Elements V, X, Z from loc. BL-1, USGS 9382-CO; W and Y from loc. BLR-1; USNM 487003-07.

AA. *Pygodus* sp. Stereo-pair showing broken Pa element, partially exposed on bedding surface of fine-grained sandstone from Jutland klippe sequence, loc. HB-6, USGS 11253-CO, USNM 487008.

AB. *Periodon aculeatus* Hadding. Two ramiform (S) elements on bedding surface of siltstone from Jutland klippe, loc. HB-6, USGS 11250-CO, X60, USNM 487009.

AC. *Drepanoistodus suberectus* (Branson & Mehl). Drepanodontiform element; same loc. as fig. E, X120, USNM 487010.

AD. *Pseudooneotodus mitratus* (Moskalenko). Upper view of this cap-shaped element. Same loc. as figs. A-D, USNM 487011.

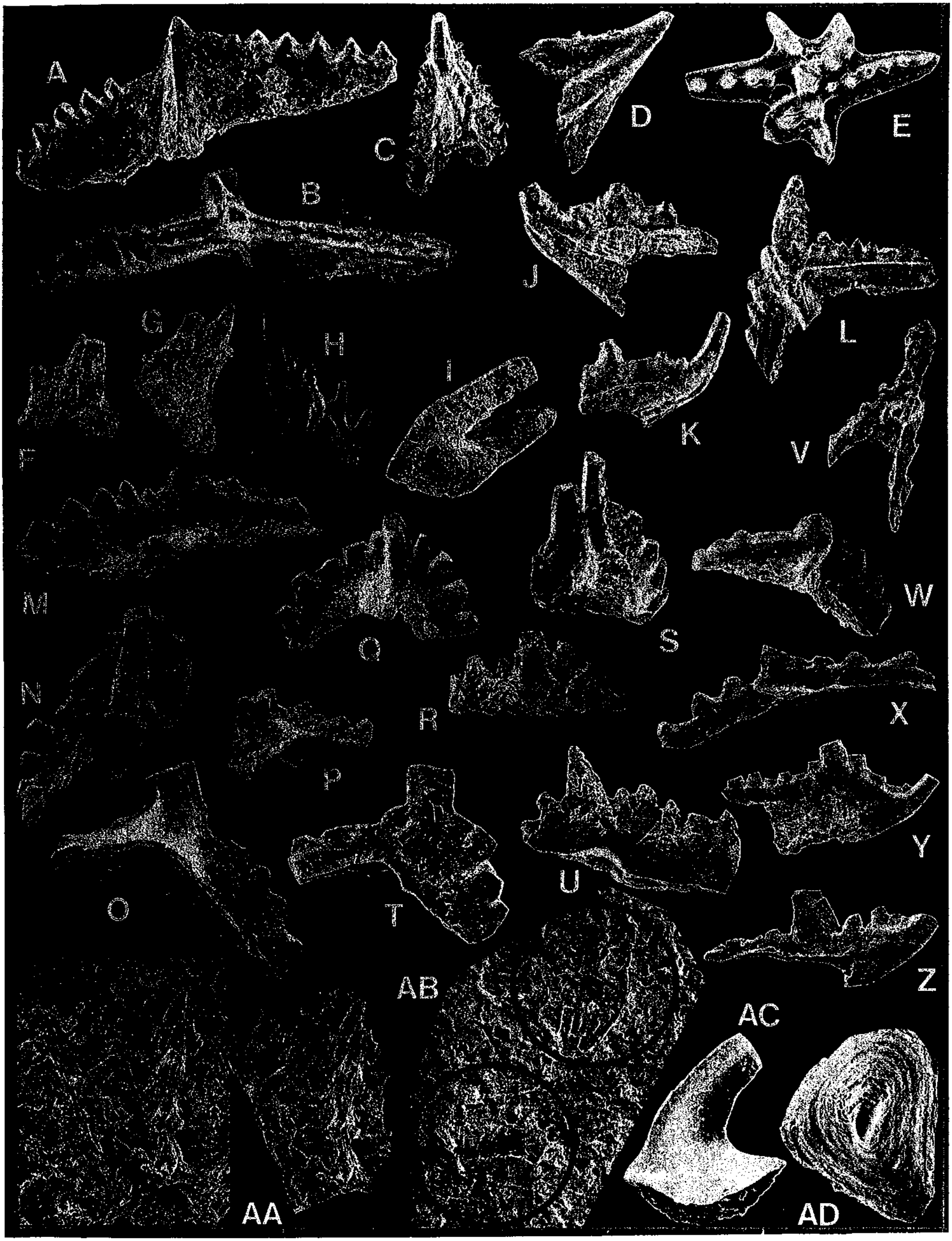
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PLATE IV

Early Devonian conodonts from northwesternmost New Jersey

A-I. *Ozarkodina remscheidensis* (Ziegler), the most abundant species in collections from Upper Silurian rocks and in most collections from lowermost Devonian rocks in New Jersey.

- A, C, D. From 1 m below top of Depue Limestone Member of the Coeymans Formation, loc. CG-2. A, C, Pa elements, inner lateral and upper views, USNM 486876, 78. D, Pb element, outer lateral view, USNM 486879.
- B. Pa element, inner lateral view, 2 m below top of Depue Limestone Member of the Coeymans Formation, loc. FL-1, USNM 486877.
- E, H. M and Sb_2 elements, inner lateral views, 4 m below top of Thacher Member of the Manlius Limestone, loc. PJS-1, USNM 486880, 83.
- F. Sa element, posterior view, 0.3 m above base of Shawnee Island Member of the Coeymans Formation, loc. CG-1, USNM 486881.
- G, I. Sb_1 and Sc elements, inner lateral views, 3 m below top of Thacher Member of Manlius Limestone, loc. MI-1, USNM 486882, 84.

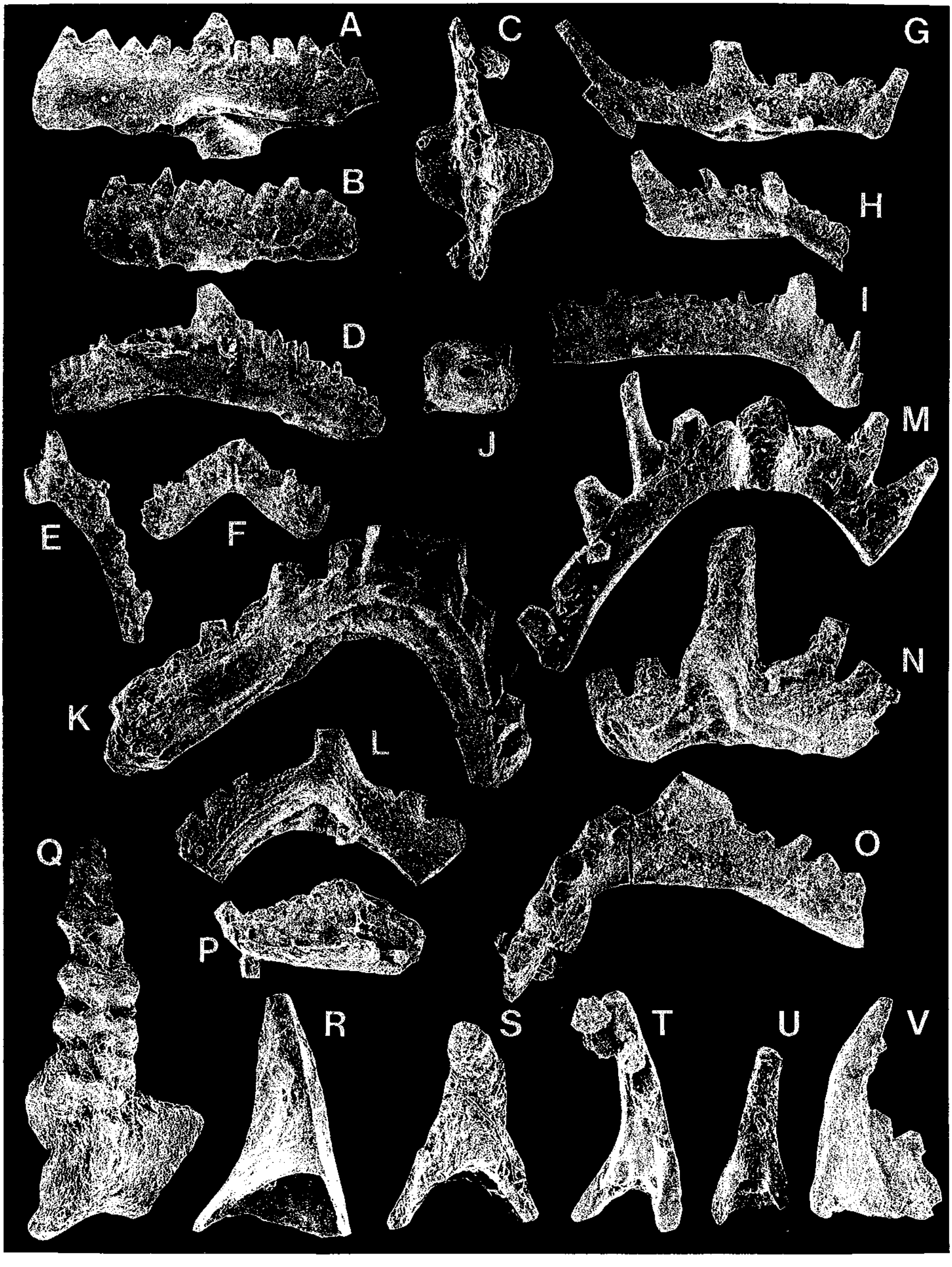
J, P. From Stormville Member of the Coeymans Formation, loc. LM-1. J, *Pseudooneotodus beckmanni* (Bischoff & Sannemann), upper view, 0.3 m above base of member, USNM 486885. P, *Belodella devonica* (Stauffer), Sb element, outer lateral view, 0.6 m above base of member, USNM 486886.

K-O. *Oulodus cristagalli* (Ziegler) from the Coeymans Formation. This species first appears in the very latest Pridolian and is an auxiliary guide to the base of the Devonian.

- K, M-O. Pb_1 (lateral view), Sa (posterior view), Sb, and Sc (lateral views) elements, 0.6 m above base of Ravena Member, loc. PJS-1, USNM 486887-90.
- L, Pb_2, lateral view, 8 m above base of Shawnee Island Member, loc. MI-1, USNM 486891.

Q-V. *Icriodus woschmidti* Ziegler from the Coeymans Formation. This species is a guide to the base of the Devonian.

- Q, R, U. Pa (upper view), Pb (postero-lateral view), and an adenticulate Sc element (inner lateral view), Shawnee Island Member (Q and U, 1 m above base; R, 0.6 m above base), loc. MI-1, USNM 486892-94.
- S. M element, inner lateral view, same collection as P, USNM 486895.
- T, V. Adenticulate and denticulate Sb elements, inner and outer lateral views, same collection as F, USNM 486896, 97.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Plant Spores from Lateral Equivalents to the Delaware Water Gap Section

Paul K. Strother and John H. Beck

Abstract. -- Lateral equivalents to sediments of Silurian age in the Delaware Water Gap in eastern Pennsylvania have produced a record of early land plant evolution based on fossil spores. The Tuscarora/Shawangunk Fm contains an assemblage of cryptospores which are thought to be the spores of land-dwelling plants somewhat similar to today's bryophyte group, the liverworts (Hepaticae). Cryptospores lack the haptotypic markings (trilete marks) that characterize spores derived from the vascular plants, the dominant terrestrial plant group today. They occur elsewhere in the Ordovician, but seem to reach their zenith during the Llandoverian when the Tuscarora sediments were laid down. Lateral equivalents to the upper members of the Shawangunk, in eastern/central Pennsylvania contain various simple trilete spores referable to *Ambitisporites* and *Retusotriletes.* These genera have been found in the sporangia of rhyniophytes in the UK, and we are therefore quite confident about their relations to the first vascular plants. The Bloomsburg Fm contains *Nematothallus,* a problematic thalloid land plant quite unlike any known plants today. This plant was perhaps a "failed" evolutionary attempt to survive on land. Upper Silurian tidal flat sediments in south central Pennsylvania contain simple triletes as well, even though Upper Wenlockian to Ludlovian assemblages outside the Appalachian Basin exhibit more morphological diversity during this interval. Sediments of Emsian age near, Flatbrookville NJ contain a poorly preserved assemblage of simple trilete spores with a few marine elements. The assemblage, described here for the first time, continues this trend of unornamented spores continuing to dominate assemblages after more complex forms had evolved elsewhere. Overall, the microfossil plant record from this region documents the existence of a pre-vascular flora which was followed by the primary radiation of the vascular plants during later Silurian and early Devonian time.

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The origin of land plants in relation to the spore record

Although there is still debate over the details of the algal-embryophyte evolutionary transition, botanists have continued to narrow down those algal groups from which all subsequent land plants[1] were derived (Graham, 1993) and something like the charaphycean green alga, *Coleochetae* is considered the likely progenitor. These earliest land plants went through a series of stages, sequentially acquiring the characteristics of hepatics, then mosses, and finally, tracheophytes. In this view, supported by the cladistic analyses of Mishler & Churchill (1984), the bryophyte groups are primitive embryophytes whose ancestors gave rise to the tracheophytes. Extant algae lack certain physiological and morphological features which enabled the primordial embryophytes to survive on land; the acquisition of a cuticle, stomata, water-conducting cells, and resistant-walled spores, together represent a major evolutionary event in the history of plant life. The subsequent development of life on the surface of this planet was certainly very closely linked

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[1] The term "land plants" is equivalent to the embryophytes, photoautotrophs with embryos, and kingdom "Plantae" Margulis & Swartz 1983. The extant embryophytes contain two basic groups, the bryophytes (liverworts, hornworts, mosses) and the tracheophytes (vascular plants). It is this later group, with its specialized water-conducting cells (tracheids) and trilete spores, that has convincingly adapted to the terrestrial habitat.

to these evolutionary changes that occurred during the Silurian interval.

For a variety of reasons, the fossil record of the algal-embryophyte transition is not terribly well known. Soft tissues, which are characteristic of aquatic organisms, do not preserve well, and we would not expect to find well-preserved examples of algae and bryophytes in most sediments. Spores, with their extremely inert walls composed of sporopollenin, are an exception to this rule. In many fine-grained siliciclastic sediments which have not been subjected to thermal metamorphism or oxidation during lithogenesis, spores and related organic fragments can be quite abundant. Spore morphology can be closely correlated with the parent plant type. During the typical life-cycle of a cryptogamic, ie. spore-bearing, plant, the continuation of the individual plant is encapsulated in this single cell. It is this general correlation that enables us to reconstruct a picture, albeit imperfect, of plant evolution based on the recovery of just the spores of those plants.

The oldest undisputed land plant, *Cooksonia*, is found in the Homerian (upper Wenlockian) of Ireland (Edwards & Feehan. 1980). *Cooksonia* is a very simple, leafless, dichotomously branched, vascular plant axis which bore globose sporangia at its tips. In North America, it is known only from the Bertie Waterlime (Pridolian) in New York (Banks 1975). *Cooksonia* sporangia have been examined since its original description from the Downtonian of Wales (Lang 1937) and they always contain trilete spores. For most of this century, simple trilete spores, when found dispersed in Silurian sediments, have been considered as proof of the existence of a *Cooksonia-like* plant. Trilete spores described from the upper Silurian of Wales (Richardson & Lister 1969) and Libya (Richardson & Ioannides, 1973) showed a progressive diversification of form, especially in ornamental sculpture and variations in wall thickness. This diversification during the later half of Silurian time, seemed to correlate well with the known record of Cooksonia and most would agree that the spore record has faithfully recorded an initial rise of tracheophytes at that time.

The earliest of the trilete spores, *Ambitisporites* Hoffman 1959, originally described from the Llandoverian, is now known from the uppermost Ordovician of Libya (Richardson 1988), considerably predating the earliest macroscopic remains of tracheophytes. Until the 1970's the occurrence of the *Ambitisporites* near the base of the Silurian was considered one of those nagging anomalies that occur in perhaps poorly dated sequences, it just did not fit the paleobotanical paradigm of the time, (e.g. Chaloner 1970). In the later half of the 1970's, reports of spore-like remains from the lower Silurian of the Appalachian Basin (Gray & Boucot 1971, Pratt et al. 1978, Strother & Traverse 1979) began to change this picture of plant evolution. The specimens from the Appalachian Basin consisted of tetrads and dyads of spore-like cells which did not display the trilete mark as proof of their tracheophytic affinity. This lead Richardson, Ford and Parker (1984) to clarify the issue by proposing a new term, cryptospores, for these fossils which are lacking the trilete mark, but are otherwise morphologically indistinguishable from tracheophyte spores. The cryptospores are also morphologically different from acritarchs, a miscellaneous organic-walled microfossil group thought to be the encysted remains of algae.

With the advent of the cryptospore concept (Richardson, Ford & Parker 1984, Richardson 1985, Strother 1991), the spore-like microfossil remains from the Silurian of eastern and central Pennsylvania could be placed into a reasonable paleobotanical framework. Basically, this opened up the possibility that we were finding remains of land plants which were were evolutionary intermediates between aquatic algal ancestors and full-fledged tracheophytes. Evidence continues to accumulate that these earliest land plants were at a "bryophyte" grade of evolution, reinforcing the theory that the tracheophytes were derived from bryophytic ancestors.

The record of cryptospores and spores from NW New Jersey and Pennsylvania

The Tuscarora Fm. -- The Tuscarora Fm of central and eastern Pennsylvania is considered to be the lateral equivalent of the lower part of the Shawangunk Fm, exposed at the Delaware Water Gap. In the greenish mudstones interbedded with quartzites of this well known ridge-forming unit, are found a diverse assemblage of cryptospores, problematic cuticles and nematoclasts (organic tubes of probable plant origin). Rare trilete spores occur in the Tuscarora (Strother & Traverse 1979), but the cryptospore tetrad, *Tetrahedraletes medinensis* Strother & Traverse 1979, is far more numerous, constituting over 60% of the specimens counted in some samples. On average, the Tuscarora assemblage is composed of 70% monads (single-celled), 27% tetrads (four attached cells) and about 2% dyads (paired cells) (Strother & Traverse 1979). Most of these cryptospores have smooth to granular walls with very little ornamentation. When ornament is present, it usually consists of rugulae or a finer reticulum covering the entire tetrad of cells.

The unit has been most thoroughly studied by Johnson (1985) who described non-marine, cryptospore taxa from a locality at Mill Hall, Pennsylvania plus one sample from Waggoner's Gap, PA, a direct lateral equivalent to the Delaware Water Gap section (Table I). In addition, simple trilete spores, attributable to *Ambitisporites* and *Retusotriletes* are found as less than 1% of the assemblage (Strother & Traverse 1979, Johnson 1985). There are two aspects of the morphology of these forms which have particular significance for plant evolution. The first is the preservation of tetrads of spores, permanently bound together. These tetrads represent the remains of the four spores produced by the reduction division (meiosis) that occurs during all plant life cycles. Their abundance seems to indicate that the plants of this era were releasing their spores into the environment at an earlier stage in development than they normally do today. In extant cryptogams (except for some hepatics) spore tetrads develop within the enclosing, protective sporangial tissues but the individual meiotic spores split apart before there are released into the environment as spores. This has lead to the conclusion that trilete spores evolved from a primitive tetrad condition through progenesis, a shift in the timing of development (Strother 1991). This macroevolutionary pattern is seen in various animal groups as an important and more general evolutionary process (Gould 1989).

The second interesting morphological artifact associated with these early cryptospores is the abundance of enclosing membranes surrounding both monads and tetrads. One explanation for

taxon	description
Tetrahedraletes medinensis	smooth-walled, tetrahedral tetrad of 4 sub-triangular spores with thickened margins
Tetrahedraletes (Nodospora) retimembrana	Tetrahedral arrangement of 4 sub-circular spores with reticulate ornament
Tetrahedraletes (Nodospora) rugosa	Tetrahedral arrangement of 4 sub-circular spores with rugose ornament
Stegambiquadrella contenta	4 loosely allied subcircular spores enclosed in a thin irregular sac
Pseudodyadospora laevigata	Permanently fused, smooth-walled dyad in without a common wall between them
Pseudodyadospora rugose	A pseudodyad (bipolar spore) with rugose ornament
Dyadospora murusdensa	True dyad with thick walls, hemispherical shape
Dyadospora murusattenuata	True dyad pair, sub-circular shaped with thin walls
Rugosphaera tuscarorensis	Rugulate ornamented monad

Table I. Cryptospore taxa described from the Llandoverian, Tuscarora Formation (Johnson 1985)

these structures is that they could represent the resistant walls of spore mother cells (SMC), the diploid sporogeneous cells that undergo meiosis to produce haploid spores. This hypothesis has implications determining the relations of monads to plant life cycles as well as influencing our thinking about the origins of the embryophytic lineage from its algal ancestors.

The Tuscarora microflora establishes that land-dwelling plants were abundant by Llandovery (lowermost Silurian) time. Most recent interpretations of this formation suggest a complex paralic to shallow shelf depositional setting with some fluvial facies (Cotter 1983), but this is based largely upon sedimentological interpretations of sandstones. Since the provenance of the interbedded muds (based on their palynomorph content) throughout the Shawangunk and Tuscarora Formations is so strongly non-marine,we a conclude that these muds were washed in from rivers that were draining into the sandy beach and near-shore shelf sites. The potentially high freshwater flux might have produced brackish water conditions which could explain the depletion in normal marine invertebrate body fossils that characterized these units. Ironically, the shales in these units do not necessarily represent marine incursions or transgressions, but carry with them a non-marine signature until the return of open marine muds in the overlying Rose Hill Fm.

The Clinton Group -- Between the quartzites of the Shawangunk/Tuscarora Fm and the redbeds of the Bloomsburg Fm, lies a heterogeneous mixture of shales and mudstones with thinner bands of Fe-rich sandstones, which has been referred to as the "Clinton Group." In the central Pennsylvania region where palyniferous samples have been collected, the sequence is, Rose Hill Sh, Keefer Ss, and Mifflintown Fm. But these formational boundaries are regional and they cannot be maintained from state to state. The Rose Hill is considered to be Telychian in age and the Bloomsburg is probably Gorstian, so the Clinton Group was deposited during Wenlockian time.

The shales of the Rose Hill represent a clear marine transgression onto the paralic deposits of the underlying Tuscarora, but at Monterey, Virginia, shallow, tidally influenced deposits contain aquatic scorpions, eurypterids, megascopic plant axes and microfossils. Some of these may have had freshwater origins, especially the plant remains. Typically, the Rose Hill palynoflora is dominated by acanthomorphic acritarchs (Cramer 1969) and chitinozoa, with only occasional trilete spores and cryptospores present. The triletes that are found are simple forms, similar to *Ambitisporites avitus*.

The Keefer Ss could represent a shallowing event within the Clinton. In a sample collected by P.K. Strother and Alfred Traverse (Penn State University) near Danville PA, the microscopic organic fraction of the Keefer was dominated by organic tissue fragments with minor sporomorphs and no acritarchs. It clearly shows the non-marine character of these shales interbedded between sandy beds. *Ambitisporites* is present as is *Velatitatras* Burgess, a membrane-enclosed cryptospore tetrad.

Above the Keefer at Fort Robinson PA, the palynoflora undergoes another change when a few acritarchs (*Leiofusa, Comasphaeridium*) return in samples from the Mifflintown Fm. The diversity of cryptospores is quite high in the Mifflintown as a whole, but no quantitative data is currently available on this unit. At Fort Robinson, *Quadrisporites* and similar forms are abundant. These planar to cross (cruciate) tetrads are extremely problematic in origin and could represent the remains of terrestrial algae rather than embryophytes. Nematoclasts, the remains of "banded" tubes and other problematic plant debris are abundant and well-preserved in the Mifflintown Fm.

The Bloomsburg Fm. -- The Bloomsburg redbeds are well known from the Delaware Water Gap section and can be traced laterally into Maryland. The plants from the Bloomsburg are dominated by *Nematothallus* and *Prototaxites*, two very problematic, terrestrial plants. *Nematothallus* described from the Schuylkill Water Gap , is a thalloid plant composed of a mat-like network of intertwined tubes (Strother 1988). Its relation to other plants is not well known, particularly since its anatomy is fundamentally filamentous and thus is in contrast to the embryophytes whose plant structure is parenchymatous, with roughly isodiametric cell structure. Strother (1988, 1993) has placed these plants and other fossils thought to be intermediate between the algae and the modern land plants into the group Paraphyta. It is likely that the Paraphyta represents a heterogeneous group of "failed"experiments in evolutionary progress toward coping with the terrestrial environment.

Sporomorphs described from an outcrop between the Schuylkill and Delaware Water Gaps as "Clinton" in age by Strother & Traverse (1979) could be of Bloomsburg age (Strother 1991). Cryptospores from this section are conspecific with Homerian (upper Wenlock) ornamented species from the type region in the UK and in the Prague Basin (Dufka in press). These include distinctive perforated cryptospores (*Confossuspora*) and the widespread forms *Dicryptosporites*, *Hispanaediscus* and *Artemopyra*. Further the the west, at Fort Robinson PA, the Bloomsburg microflora, recovered from grayish shale intercalated into the organically barren redbeds, contains elements similar to the underlying Mifflintown Fm. At Roundtop Hill, MD, the Bloomsburg contains well preserved examples of the cryptospores *Laevolancis*, *Dyadospora*, and numerous tetrads in addition to small trilete spores related to *Retusotriletes*.

Numerous lines of sedimentological and paleontological evidence, including paleosol horizons, indicate that the Bloomsburg is a terrestrial deposit. The predominance of oxidized sediments throughout the formation preclude the preservation of spores and plant remains, however, and those described here tend to come from exceptional reduced beds, or from reduced shales in transition to over or underlying units.

The Wills Creek Fm. -- Twelve samples were collected through an 8m section in the Wills Creek Fm at Roundtop Hill, Maryland, a site known for its structural geology (Glaser 1989). The unit contains salt hoppers and algal laminites and is thought to represent cyclic deposition within a marly tidal flat. The signature of the extracted organic fraction is decidedly non-marine, these sediments were receiving terrestrial debris, with only minor marine influence. Fig.1 shows the distribution of spores, cryptospores and "leiospheres" throughout the section in relation to supposed incursions of transgressive limestone beds, marking cycle boundaries. The provenance of leiospheres is unknown, but acritarchs of known marine origin are quite rare throughout. (Of over 2500 specimens counted, only 31 acritarchs were found, 15 of which were from a single sample near the top of the section).

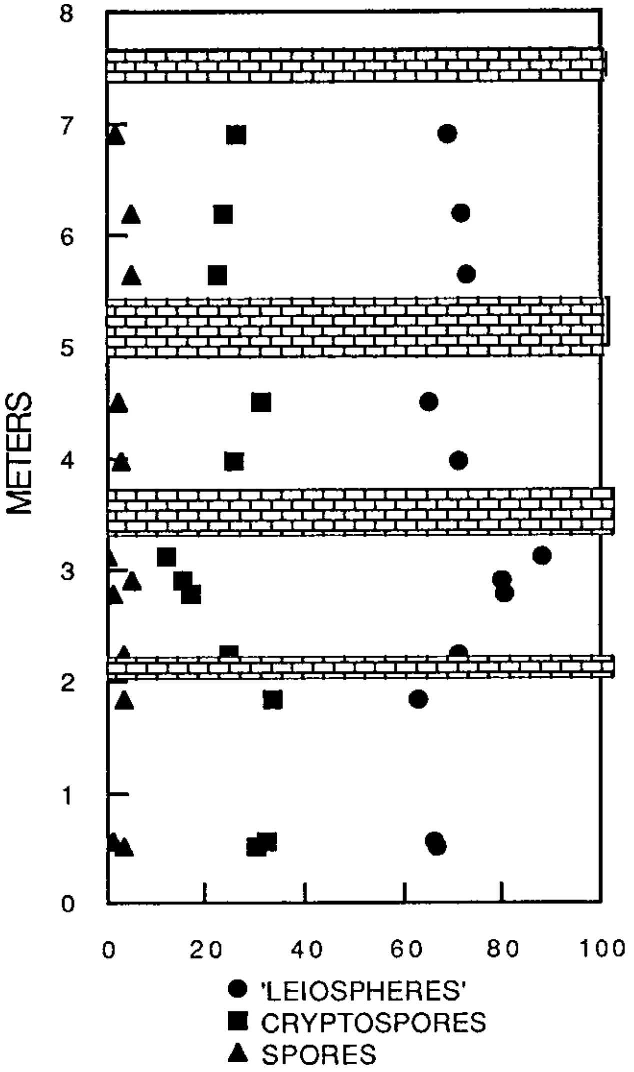

Figure 1. Palynomorph distributions throughout the Wills Creek section at Roundtop Hill MD

Table 2 shows the non-marine sporomorphs composing the Wills Creek assemblage. Cryptospores, on average, constitute 24% of the total sporomorph count (range 12 to 33%); trilete spores are considerably fewer at 3% (<1 to 5% range). This demonstrates one of the more general trends seen in the Silurian sporomorph record : a gradual shift in dominance of cryptospores to that of trilete spores. By the end of Silurian time, non-marine

	genus (# of species)	description
Cryptospores		
	cf. *Rimosotetras*	partially adherent simple tetrad
	cf. *Tetrahedraletes*	tetrahedral tetrad of unornamented spores
	Quadrisporites (2)	cruciate tetrad, possibly algal
	other tetrads	undescribed tetrads
	Dyadospora (2)	simple smooth-walled forms
	Hispanaediscus	ornamented cryptospore monad
	Laevolancis	asymmetric monad
	new monads (3)	cryptospore monads with attachment scars
Spores		
	Ambitisporites (3)	simple triletes with marginal thickening
	Retusotriletes	simple triletes with curvaturae
	new trilete genera (2)	simple triletes without marginal thickenings

Table 2. Cryptospore and spore taxa from the Wills Creek Formation at Roundtop Hill

components are approximately split equally between these two groups, and cryptospores probably decline rapidly during the lower Devonian (Gensel *et al.* in prep.). Secondly, none of the sporomorphs represented in Table 2 are ornamented save for *Hispanaediscus*. This observation is somewhat at odds with age equivalent sequences in Avalonia and the Welsh Basin where ornamented forms become abundant in the Homerian. Perhaps the restrictive depositional setting of the Wills Creek sediments was not conducive to these more recently evolved plant types.

The Esopus Fm. -- A calcareous siltstone from the Esopas Fm. 3.5km NE of Flatbrookville New Jersey contains organic debris with a few simple spores and acritarchs. Preservation is poor, but several acritarchs and spore types were recognized including, *Ammonidium microcladum* Lister, *Diexallophasis* sp., *Cymatiosphaera* sp., and ? *Ambitisporites*. Too few specimens were encountered for relative abundance estimates, but the absence of cryptospores in these Devonian rocks is consistent with the hypothesis that the cryptospore-producing plants which dominate the Silurian landscape were displaced by the rising lineage of tracheophytes during the Devonian Period. The recovery of palynomorphs in 2 of 2 samples examined, indicates clearly that further collection and examination of the upper Silurian/lower Devonian units in NW New Jersey could prove quite fruitful.

Discussion and Conclusions

Lateral equivalents to the Silurian and Lower Devonian sequence at the Delaware Water Gap contain an important record of plant evolution based on their content of sporomorphs and plant fragments. The earliest units are dominated by cryptospores, particularly simple tetrads and dyads like *Tetrahedraletes* and *Dyadospora.* Membrane-enclosed cryptospores reach their zenith during the Llandoverian. Cryptospores from the Llanvirnian (lower Middle Ordovician) of Saudi Arabia are often preserved with enclosing membranes (Strother *et al.* 1994, Strother et al. submitted). Together with evidence from membrane-enclosed, non-marine algal cysts from the Middle Cambrian of Arizona (Strother in prep.), this character may represent links to algal ancestry.

The loss of enclosing membranes throughout the remainder of the Silurian with the subsequent rise of true trilete spores are part of a more general picture of evolutionary displacement of the cryptospores by the trilete spores during this time. This picture of changes in the sporomorph flora is more complicated than that envisioned either by the study of neontology or megafossil paleobotany alone. Recent ultrastructural evidence linking cryptospore dyads to hepatics (Taylor in press) seems to support both morphological and cladistic studies that propose certain bryophyte groups to be primitive. Trilete spores probably arose not *de novo* from an embryophytic group, but from the protogenous development of a *Tetrahedraletes-like* cryptospore tetrad. This has been essentially documented "taxonomically" in the sequence *Velatitetras-Tetrahedraletes-Rimosotetras* which proceeds from membrane-encloded forms to free, but tightly bound forms to the last, more loosely attached tetrad form. Interestingly, such a sequence to produce the "first" trilete spore (*Ambitisporites vavrdovii*) is not seen as a stratophenetic sequence, since all these forms occur with the Llandoverian Tuscarora Formation.

Peak diversity for the cryptospores may also have occurred during Tuscarora time, but a wide variety of morphologies of one, two and four-celled forms persist throughout the Silurian of this area. Trilete spores from the Appalachian Basin seem to be morphologically simpler than their age equivalent counterparts in the Prague and Welsh Basins. Whether this is due to evolutionary factors or sampling biases induced by depositional settings is not known. In either case, we need to exercise caution when using palynomorphs for biostratigraphic control. The microflora recently discovered from the Emsian Esopas Fm is a case in point, for none of its few elements is distinctly Devonian in character.

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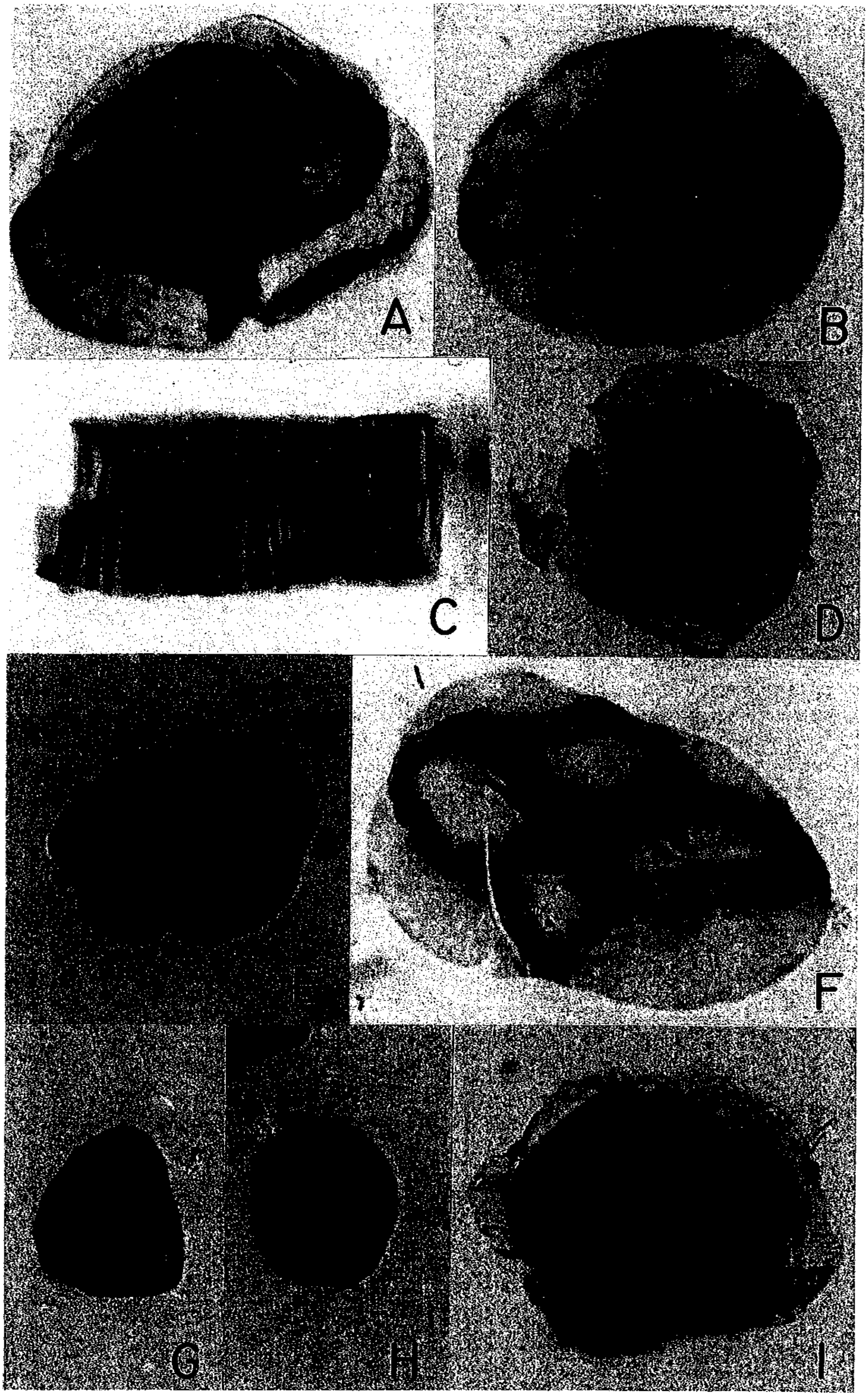
Plate I

A. *Tetrahedraletes* cf. *T. retimembrana*, Tuscarora Fm, 1500x. **B.** *Pseudodyadospora* sp., Tuscarora Fm, 1500x. **C.** *Porcatitubulus spiralis*, Williamsport memb., Bloomsburg Fm, this is a typical nematoclast, presumedly a fragment of a nematophytic plant, 1000x. **D.** Undescribed monad cryptospore with surrounded by an enclosing membrane, Tuscarora Fm, 1000x. **E.** *Dicryptosporites radiatus*, Williamsport memb., Bloomsburg Fm, 1000x. **F.** *Tetrahedraletes (Nodospora) burnhamensis,* Tuscarora Fm, 1500x. **G.** *Ambitisporites dilutus*, Williamsport memb., Bloomsburg Fm, 1000x. **H.** *Confussaspora reniforma*, Williamsport memb., Bloomsburg Fm, 1000x. **I.** *Velatitetras laevigata*, Tuscarora Fm, a cryptospore tetrad enclosed within a membrane, 1000x.

Plate II

A. Undescribed cryptospore tetrad similar to *Rimosotetras* sp. Burgess, Wills Creek Fm, 1000x. **B.** Undescribed trilete spore with microreticulate sculpture, Mifflintown Fm, Fort Robinson PA, 1000x. **C.** *Rugosphaera cerebra*, a rugulate cryptospore monad, Wills Creek Fm, 1000x. **D.** Undescribed cryptospore tetrad, planar and possibly related to *Quadrisporites*, Mifflintown Fm, Fort Robinson PA, 1000x. **E.** *Tetrahedraletes medinensis*, Tuscarora Fm, 1000x. **F.** *Nematothallus lobata*, a thalloid nematophyte, this plant, although problematic, was probably the predominant plant living on the land surface during Silurian time, Bloomsburg Fm, Port Clinton PA, 5x. **G.** (?) *Retusotriletes* sp., Wills Creek Fm, 1000x. **H.** *Ambitisporites dilutus*, Keefer Ss, near Danville PA, 1000x. **I.** *Laevolancis* sp., this monad cryptospore is quite common throughout the Silurian section, Bloomsburg Fm, Roundtop Hill MD, 1000x. **J.** Three palynomorphs from the Esopas Fm, near Flatbrookville NJ, demonstrate the three basic palynomorph types found in these early plant assemblages: ACRI-acanthomorph acritarchs such as this one are evidence of marine deposition, LEIO- leiospheres are simple cysts which can be of heterogeneous origin, SP- trilete spore such as this cf. *Punctatisporites*, are derived only from land plants and indicate a terrestrial source. It is possible that these particular palynomorphs are reworked from earlier sediments. ca. 1000x. **K.** *Diexallophasis* sp., an acritarch, most probably the cyst of a marine alga, Esopas Fm, near Flatbrookville NJ, 1000x.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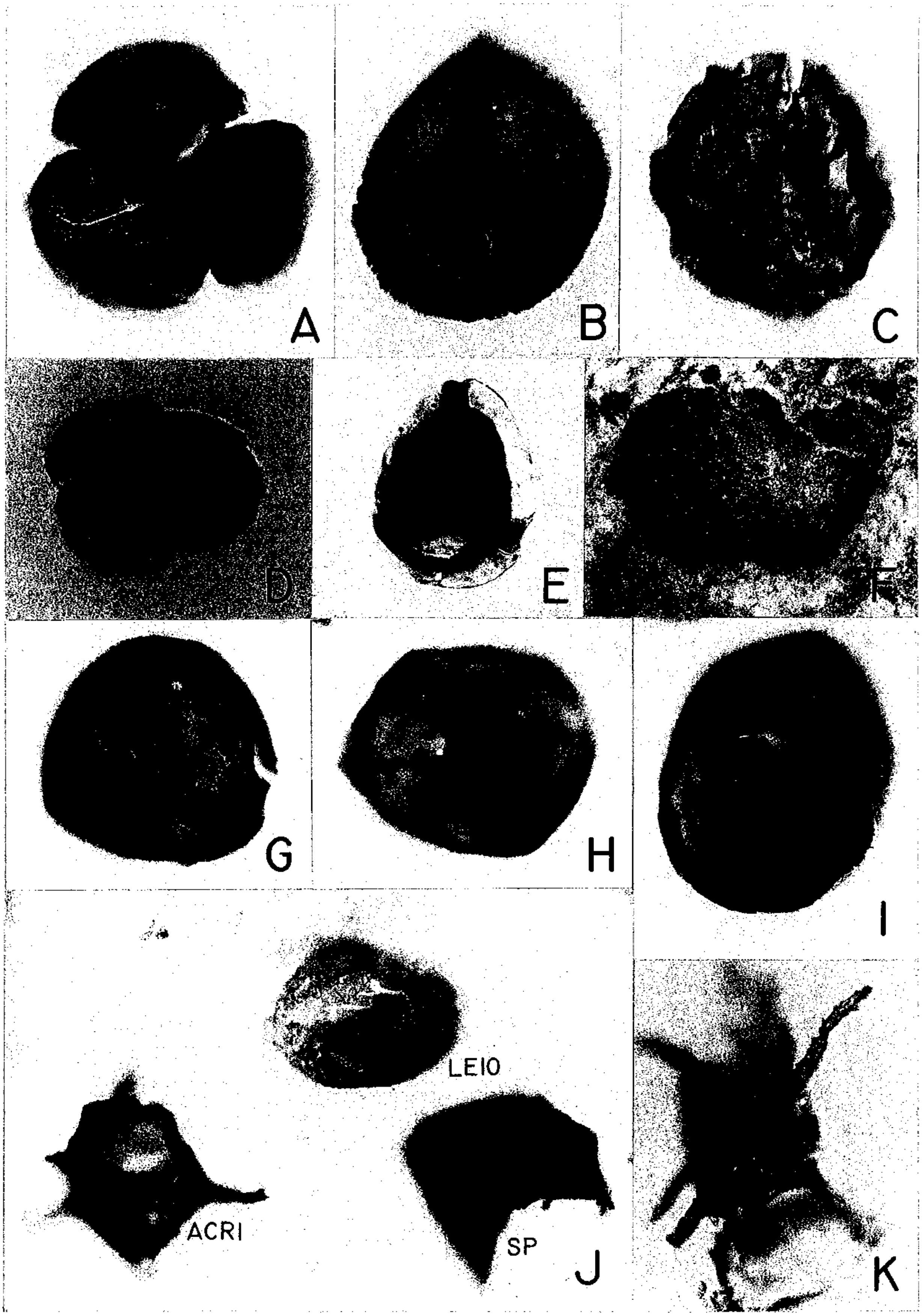
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The *Conulariida* of New Jersey

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ABSTRACT

The New Jersey State Museum is the respository for twenty-eight conulariids (assigned to twelve catalogue numbers) that have been collected from five stratigraphic levels in New Jersey. With the exception of one specimen unidentified beyond Phylum Conulariida, the remainder are distributed among three species. The Museum's holdings include the holotype and two paratypes of ***Reticulaconularia sussexensis*** (Herpers) as well as numerous Devonian conulariids from the Hamilton Group of adjacent Pennsylvania.

INTRODUCTION

Conulariids are an extinct group of invertebrates with a four-sided, pyramidal exoskeleton and a stalk by which the individual could attach itself to the substrate. The exoskeleton is an elongate framework of calcium phosphate rods which may or may not exhibit secondary ornamentation such as nodes or spines. They were exclusively marine and are now believed to have been restricted to rocks of the Lower Ordovician through Upper Triassic Systems.

Following an intensive investigation of assignable Devonian through Mississippian specimens, Babcock and Feldman (1986) proposed acceptance of Phylum Conulariida Miller & Gunley 1896, excluding organisms such as hyoliths, tentaculitids, styliolinids which defy systematic assignment. The removal of conulariid-like fossils as well as the resolution of ambiguous or duplicative morphologic terminology has resolved some of the confusion surrounding these rare, but sought after fossils.

Taxonomic differentiation of the Conulariida is based solely on external physical characteristics since knowledge of soft anatomy is extremely scarce. Components critical to genus and species identification are number of rods per centimeter, rod articulation style, percentage of rods that meet at midline, presence or absence of secondary ornamentation, and rod angle.

The goals of this paper are two-fold. First, to review the extent and scope of New Jersey Conulariida housed in The New Jersey State Museum, and, second, to foster interest in these little known organisms.

GEOLOGIC SETTING

Although the Conulariida are known from the Lower Ordovician through the Upper Triassic Systems, the corresponding strata in New Jersey are not all conducive to conulariid collection. Pennsylvanian and Mississippian rocks are entirely missing, and the Newark Supergroup - partially assignable to the Triassic - is of non-marine origin.

Appropriate Paleozoic strata occur in three loci - a relatively narrow southwest to northeast trending belt paralleling the Delaware River Valley in Sussex County, the Green Pond Mountain outlier, and the Ordovician Martinsburg and Jacksonburg (formerly the Trenton Limestone) Formations situated northward from Hunterdon County and occupying portions of the upper left quadrant of the state.

SYSTEMATIC PALEONTOLOGY

Babcock and Feldman (1989) have reduced the proliferation of Devonian and post-Devonian North American species-level taxa from sixty-nine to twenty-eight, assignable to three genera - ***Conularia*** Miller, ***Paraconularia*** Sinclair, and ***Reticulaconularia*** Babcock and Feldman. Only nine currently valid species are appropriate for New Jersey conulariid identification:

Conularia desiderata Hall
Conularia elegantula Meek
Conularia milwaukeensis Cleland
Conularia pyramidalis Hall
Conularia ulsterensis Howell
Conularia undulata Conrad
Paraconularia alpenensis Babcock & Feldman
Reticulaconularia penouili (Clarke)
Reticulaconularia sussexensis (Herpers)

Ordovician and Silurian conulariids have not been similarly studied at this time. It seems premature to make any generalizations about the number of valid genera or species.

The following remarks will address only the noteworthy attributes of catalogued specimens from New Jersey. For the sake of brevity, readers are urged to refer to published species descriptions. Numerous conulariids from the Marcellus and Mahantango Formations exposed in the Pennsylvania portion of the Delaware Water Gap National Recreation Area are known. Specimens attributed to ***Conularia undulata*** Conrad and ***Conularia desiderata*** Hall are catalogued in the New Jersey State Museum collections, but they will not be discussed in this paper.

Phylum Conulariida Miller & Gunley

Conulariida, gen. and sp. undet.

NJSM 14993

Remarks: Single specimen associated with diminuitive fauna. Impression of single, partial face. Very difficult to see without magnification. Rods closely spaced and well defined. No midline evident. Nodes absent. Fractured.

Occurrence: Parris and Albright (1980) locality 39. East side of County Route 521. Small excavation about 1 mile north of Dingman's Bridge, Sandyston Township, Sussex County, New Jersey.
Collected by Shirley S. Albright.
Hamilton Group, Marcellus Formation.
Site closed to collecting (property of The Delaware Water Gap National Recreation Area).

Conularia trentonensis Hall

NJSM 6102

Remarks: 9 fragments, 3 containing conulariid fragments. All specimens are partial faces. Rod style and spacing is apparent, but midlines are not evident. Faces appear to be unevenly fractured. Associated with brachiopod and trilobite fragments. Matrix is very fossiliferous.

Occurrence: Weller (1903) locality 174A, the Jacksonburg Section. A hill about 580 feet in elevation on the property of Mr. E.J. Hough, just back

of the mill at Jacksonburg, near Blairstown, Warren County, New Jersey. Specimens were found in 4 of the 61 described units.
Collected by Stuart Weller.
Jacksonburg Formation.
Ordovician.

NJSM 6106
Remarks: 5 fragments, 3 containing conulariid fragments. All specimens are partial faces. One specimen appears to have heavily reticulated exoskeleton. Associated with plentiful invertebrate fossils, including one gastropod. Rods visible but midlines are not exposed.
Occurrence: Weller (1903) locality 174A. See above.

NJSM 6107
Remarks: 4 fragments, all containing conulariids. At least 2 specimens display fairly complete single faces with midlines. Rods distinct. Heavily fractured.
Occurrence: Weller (1903) locality 79A. About 7/8 mile a little west of north from Beaver Run, west of Hamburg, Sussex County, New Jersey.
Collected by Stuart Weller.
Jacksonburg Formation.
Ordovician.

Conularia pyramidalis Hall

Conularia huntiana Hall
Conularia lata Hall
Conularia huntana (sic) Hall

NJSM 12559
Remarks: 1 specimen. Negative with two complete faces. Corner groove evident. Apical area broken. Inflected gothic arch articulation. Complete specimen would have attained length greater than 4 cm..
Occurrence: Parris and Albright (1980) locality 7. 1.7 km. southwest of Wallpack Center in roadcut across from Battali's Campground, Walpack Township, Sussex County, New Jersey.
Collected by David Parris, Kenneth Cruikshank and Shirley Albright.
Port Ewen Formation.
Devonian.
Site closed to collecting (property of Delaware Water Gap National Recreation Area). Covered with slope retention wall.

Reticulaconularia sussexensis (Herpers)

Conularia sussexensis Herpers
Conularia gaspesia Sinclair

NJSM 10749 (HOLOTYPE)
Remarks: Single complete individual in two pieces. Cast and mold in concretionary matrix. Apex broken. Complete ornamentation evident. 3 cm. long. Inflected gothic arch articulation. Rods abut at midline. Three dimensional preservation.
Occurrence: Millville, Montague Township, Sussex County, New Jersey.
Collected by Henry Herpers.
Esopus Formation.
Lower Devonian.

NJSM 10750 (PARATYPE)
Remarks: 2 small individuals on same rock. Probably a cluster due to proximity and orientation of specimens. In concretionary matrix. One specimen well preserved with full species characteristics visible, but second specimen very weakly defined.
Occurrence: Same as above.

NJSM 10751 (PARATYPE)
Remarks: 3 fragments, all with conulariids. Largest specimen severely flattened with one face displaying non-abutting rods while other faces exhibit rods meeting at midline.
Occurrence: Same as above.

NJSM 10806
Remarks: 5 fragments, 4 with conulariids. One excellent, small specimen with three-dimensional preservation. Exoskeleton shows evidence of repair of severe fracture between aperture and apex. Other specimens badly weathered.
Occurrence: Montague, Sussex County, New Jersey
Collected by Henry Herpers.
Esopus Formation.
Lower Devonian.

NJSM 12225
Remarks: 3 fragments of single specimen. Concretionary. Unremarkable.
Occurrence: Parris and Albright (1980) locality 165. On Weider Road, near County Route 521, Montague Township, Sussex County, New Jersey.
Collected by David Parris.
Esopus Formation.
Lower Devonian.

NJSM 14960
Remarks: 2 pieces of separate concretions, with 4 individuals. Two specimens closely associated and may be clustered. Excellent preservation of faces. Apex visible on one specimen. Reticulation especially evident.
Occurrence: Opposite Mashipacong Island, on ridge road that intersects Mashipacong Road, 580-600 foot contour, Sussex County, New Jersey.
Collected by Don Monteverde.
Esopus Formation.
Lower Devonian.
Site closed to collecting (property of Delaware Water Gap National Recreation Area).

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STRATIGRAPHIC AND PALEONTOLOGIC OVERVIEW OF THE UPPER LOWER AND MIDDLE DEVONIAN, NEW JERSEY AND ADJACENT AREAS

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INTRODUCTION

Upper Lower and Middle Devonian rocks of New Jersey and adjacent areas of New York and Pennsylvania represent a broad spectrum of non-marine and shallow marine to basinal, carbonate- and siliciclastic-dominated environments. This diversity/variety is reflected in the faunas and paleoecology of the Oriskany, Esopus, Schoharie, Onondaga, and Marcellus Formations, which are exposed along the main Devonian outcrop belt (northwestern New Jersey); equivalent units and additional overlying Middle Devonian strata occur in the Green Pond-Skunnemunk Outlier in north-central New Jersey and southeastern New York (see Figure 1). Characteristic Middle Paleozoic brachiopod-dominated faunas, with or without bryozoans, corals, trilobites, molluscs, and echinoderms are typical of parts of the marine succession in New Jersey. Other marine strata, however, are barren of body fossils and may feature uncommon to abundant ichnofossils or be barren of any fossil traces or remains. Non-marine strata may feature plant fossils.

Throughout the Paleozoic Era the eastern interior of North America was flooded by a relatively shallow epicontinental sea, bordered on its continental margin by tectonic highlands of the Appalachian Mountains. The eastern margin of this sea, adjacent to the mountain belt, was an elongate, deeper water trough termed the Appalachian Basin. During times of increased tectonism and mountain building on the eastern margin of North America (e.g., Ordovician Taconic Orogeny, Devonian Acadian Orogeny, Pennsylvanian Alleghenian Orogeny) the Appalachian Basin became an active and dynamic foreland basin.

The Devonian Period was a time of major transitions in the Appalachian Basin and the Eastern Interior of North America. Earliest Devonian carbonate-dominated environments (Helderberg Group) were succeeded by withdrawal of the interior seaway (Wallbridge Unconformity; Sloss, 1963) and subsequent deposition of widespread, transgressive quartz arenites (Oriskany Formation and equivalents). Overlying fine- to medium-grained siliciclastics (Esopus Formation) mark the onset of tectonism during the Acadian Orogeny. A subsequent changeover to increasingly carbonate-dominated deposition (Schoharie Formation) culminated in widespread limestones of the coeval Onondaga and Buttermilk Falls Formations. This pattern of an initial abrupt transition from clean carbonates-quartz arenites to siliciclastics followed by a gradual return to more carbonate-dominated rocks characterizes the first two tectonically-active to quiescent "tectophases" of the Acadian Orogeny in eastern North America (Ettensohn, 1985).

The Devonian faunas of the Appalachian Basin were affected by tectonic, eustatic, and climatic effects that altered the paleoecology of the Eastern Interior of North America. The fossil record shows that marine paleocommunities remained relatively stable through blocks of time (millions of years) during which little evolution or immigration occurred. These intervals of stability were disrupted by relatively short episodes (ca. 10-100 kyr) of major restructuring of the biofacies with significant rates of extinction, evolution, and immigration.

STRATIGRAPHIC AND PALEONTOLOGIC OVERVIEW

The stratigraphy and paleontology of upper Lower and Middle Devonian rocks in New Jersey have received little recent attention (however, see Spink, 1967; Albright, 1987). Better exposure in the adjacent states of New York and Pennsylvania has led to more detailed study of these rocks, which overlie the Wallbridge Unconformity at the base of the Kaskaskia Supersequence (Sloss, 1963). Ver Straeten and Brett (1995) present a review and synthesis of the post-Wallbridge Lower and Middle Devonian of eastern New York, and examine its sequence stratigraphic and tectonic frameworks. In eastern Pennsylvania, parts of the succession have been examined in detail by Inners (1975), Epstein (1984), Rehmer (1976) and Johnsen (1957).

Northwestern New Jersey Outcrop Belt

Oriskany (Ridgely) and Glenerie Formations. Overlying the Wallbridge Unconformity or its lateral conformity are sandstones of the Oriskany Formation (=Ridgely Formation of Pennsylvania) and laterally equivalent cherty limestone-dominated strata of the Glenerie Formation. These two facies interfinger along parts of the New Jersey outcrop belt. Spink (1967, p. 184-185) reports that the sand-dominated Oriskany facies characterize the southwestern part of the New Jersey outcrop belt along the Delaware River; limestone facies typify the northeastern area into New York State. Lower strata assigned to the Glenerie-Oriskany succession in New Jersey feature the trilobite *Corycephalus dentatus* and is the lateral equivalent of the pre-Oriskany/pre-Wallbridge Port Jervis Formation of southeastern New York.

The Oriskany Formation in northwestern New Jersey is characterized by calcareous, medium- to thick-bedded, quartz pebble conglomerate and medium- to coarse-grained quartz sandstone (Monteverde,

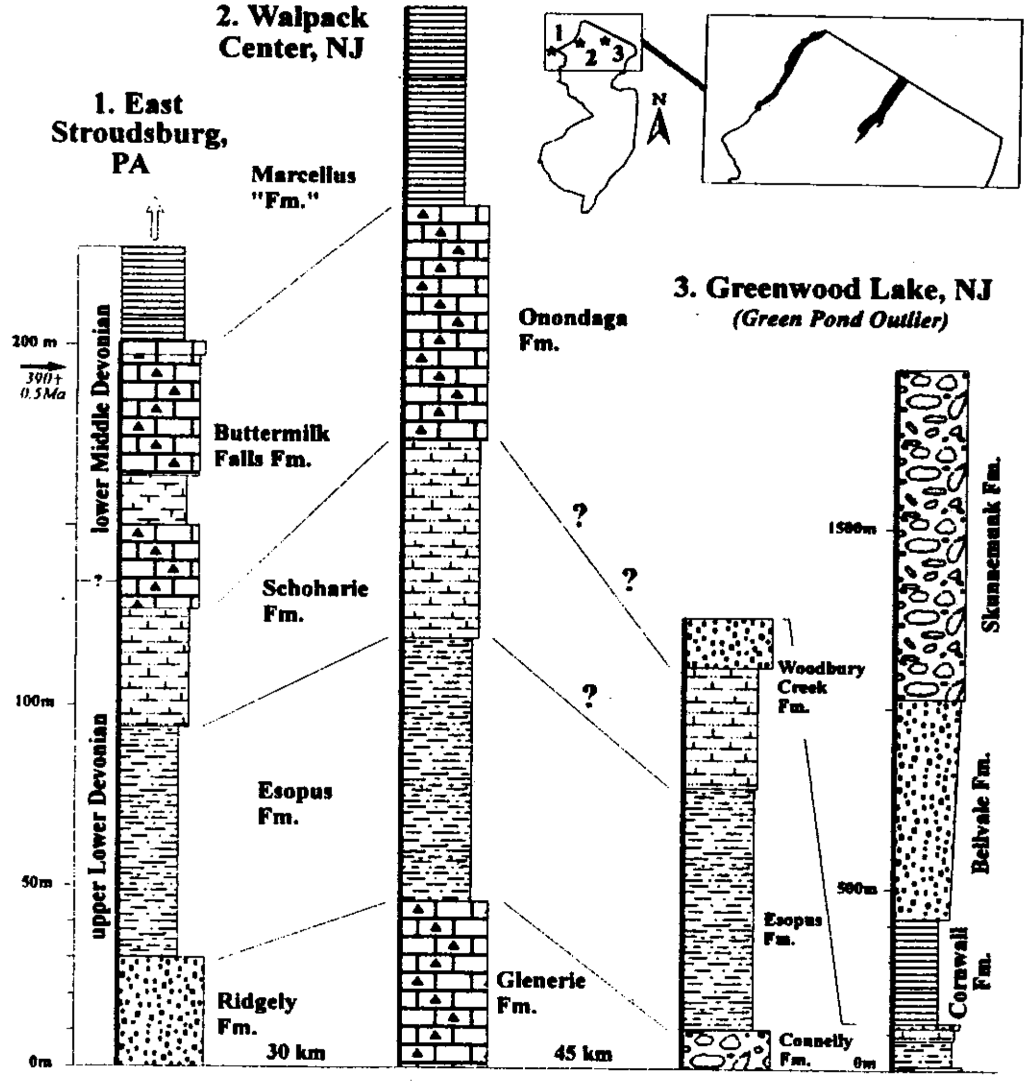

Figure 1. Upper Lower and Middle Devonian outcrop map and stratigraphic columns of northern New Jersey and vicinity. Map after Johnson (1950). Note that an unknown thickness of pre-Wallbridge Unconformity strata are included in the Glenerie-Oriskany at localities 1 and 2. Stratigraphic thicknesses after CAV (field notes), Rickard (1989), Rehmer (1976), Johnsen (1957), Inners (1975), Boucot et al. (1970), and Herman and Mitchell (1991).

1992). The unit is generally well sorted, and features abundant brachiopods. The laterally equivalent Glenerie Formation is composed of medium to dark gray, fossiliferous, thin- to medium-bedded fine-grained, cherty limestone.

The Oriskany and Glenerie Formations represent relatively shallow marine, shoreface to shelf environments. Both units are well known for their abundant faunas. Large, robust fossils, dominated by brachiopods, characterize the shallower, sand-rich Oriskany facies. A highly diverse assemblage of brachiopods, trilobites, bryozoans, bivalves, gastropods, and other forms is typical of the more offshore limestone facies of the Glenerie; Clarke (1900) described 113 fossils from the Glenerie Limestone at Becraft Mountain in the central Hudson Valley of New York. Common forms found in the Oriskany and Glenerie Formations in northwestern New Jersey include the brachiopods *Acrospirifer murchisoni*, *Costispirifer arenosus*, *Leptocoelia flabellites*, *Meristella lata*, and *Rhipidomella oblata*.

Esopus Formation. The relatively shallow marine facies of the Oriskany and Glenerie Formations are overlain by relatively thick (up to ca. 155 m), fine- to medium-grained siliciclastics of the Esopus Formation. Non-calcareous, dark-gray shales, mudstones, and argillaceous siltstones with minor fine-grained sandstones characterize the Esopus "Shale" in New Jersey, New York, and eastern Pennsylvania. The strata generally appear highly bioturbated (with profuse *Zoophycos* trace fossils) and homogenous. Due to poor exposure along the New Jersey outcrop, the Esopus is not well differentiated. However, three members can generally be recognized along the main outcrop belt in eastern Pennsylvania and southeastern New York State (Rehmer, 1975; Ver Straeten and Brett, 1995): 1) a lower silty, chert-rich unit that commonly features K-bentonites (Sprout Brook Bentonites of Ver Straeten et al., 1993, in review); 2) a middle shale-dominated member; and 3) an upper siltstone to fine sandstone-dominated member.

The dark gray shales to siltstones of the Esopus Formation were deposited under relatively oxygen-poor, basinal conditions. As a result, the strata are generally poorly fossiliferous; although trace fossils may be abundant (e.g., *Zoophycos* and *Chondrites*; see below), shelly fossils are rare to uncommon in the Esopus along the main outcrop belt (see outlier discussion below). Characteristic fossils of the Esopus Formation along the northwestern New Jersey outcrop belt include the brachiopod *Pacificocoelia acutiplicata*, conulariids, and *Zoophycos* and other trace fossils

Schoharie Formation. The Schoharie Formation of northwestern New Jersey consists of medium dark gray calcareous mudstone, siltstone, argillaceous limestone, with minor amounts of sandstone to the southwest (Inners, 1975). Two subdivisions are recognizable in New Jersey and eastern Pennsylvania; a lower massive, medium dark gray, pyritic, calcareous mudstone and an upper medium dark gray, argillaceous limestone to calcareous mudstone and sandy siltstone. These are equivalent to a lower unnamed member (formerly Carlisle Center Member; see Ver Straeten and Brett, 1995) and two upper members (Aquetuck and Saugerties Members) of the Schoharie Formation in the Hudson Valley of New York. The base of the Schoharie Formation is reportedly marked in southeastern New York, New Jersey, and easternmost Pennsylvania by a distinctive, shell-rich bed of *Pacificocoelia acutiplicata*, which generally coincides with the lowest occurrence of calcareous strata above the Esopus Formation (Johnsen, 1957).

The Schoharie Formation, especially in its upper part, is distinctly more fossiliferous than the underlying Esopus Formation. This is associated with a general shallowing-upward trend through the formation, and possibly a decrease in siliciclastic sedimentation rate. Johnsen (1957) reports the brachiopods *Pacificocoelia acutiplicata*, *Atrypa reticularis*, and unidentified spiriferids

Onondaga-Buttermilk Falls Formations. The terms "Onondaga" and "Buttermilk Falls" are regional names applied to a coeval limestone-dominated lithosome of Middle Devonian age in New York, New Jersey, and eastern Pennsylvania. The Onondaga Limestone of eastern New York consists dominantly of fine to coarse-grained, cherty to non-cherty limestone. The equivalent strata in New Jersey and eastern Pennsylvania are similar, but appear more argillaceous and thicker overall.

The Onondaga Formation is poorly exposed in southeastern-most New York and New Jersey. Most of the knowledge of these strata in the New Jersey area is from the laterally equivalent Buttermilk Falls Formation near Stroudsburg, Pennsylvania, where the formation totals 83 m in thickness. Three to four member-level subdivisions of the Buttermilk Falls Limestone have been recognized in the Stroudsburg area (Epstein, 1984; Inners, 1975): 1) a lower, cherty, medium to fine-grained limestone unit that features large crinoid columnals (Foxtown Member); 2) overlying fossiliferous, calcareous shale and argillaceous limestone (McMichael Member); 3) a third subdivision (Stoudsburg Member) of fine- to medium-grained, very cherty limestone, with a prominent K-bentonite near the top (Tioga B of Way et al., 1986); and 4) an upper unit of medium-grained, fossiliferous, less cherty strata (Echo Lake Member of Inners, 1975). These four members are the lateral equivalents of four members of the Onondaga Formation of New York (Ver Straeten and Brett, 1994; Brett and Ver Straeten, 1994; Edgecliff, Nedrow, Moorehouse, and Seneca Members). The more argillaceous and deeper-water facies of the Buttermilk Falls Limestone is in many ways similar to the Onondaga Limestone in central New York (e.g., central Finger Lakes region), except for its greatly increased thickness (ca 83 m vs. 24 m, Stroudsburg, PA and Canoga, NY, respectively).

The fauna of the Onondaga-Buttermilk Falls Limestones in New Jersey and adjacent areas is characterized by common brachiopods (including *Leptaena rhomboidalis, Atrypa reticularis, Acrospirifer varicosus*, and the chonetid *Hallinetes lineata*), trilobites (e.g., *Odontocephalus selenurus*), small rugose corals, and in the lower member, large crinoid stem pieces (Inners, 1975).

Marcellus "Shale" ("Union Springs and Mount Marion-Oatka Creek Formations"). The highest Devonian strata exposed along the main outcrop belt in New Jersey consist of black shales assigned to the Middle Devonian Marcellus "Shale." These strata in New York have recently undergone revision (Ver Straeten et al., 1994, in prep.; see Ver Straeten and Brett, 1995) wherein the Marcellus Shale of New York is raised to "subgoup" status and is subdivided into lower and upper formation-level units (lower=Union Springs Fm.; upper=coeval Mount Marion-Oatka Creek Fms.). The Union Springs Formation in eastern New York features a unique fauna (including the brachiopod *Variatrypa arctica*) that is distinct from those of the underlying Onondaga and overlying remainder of the Hamilton Group (for discussion, see Ver Straeten et al., 1994; Ver Straeten and Brett, 1995). The classic fauna of the Middle Devonian Hamilton Group first occurs in the overlying Mount Marion-Oatka Creek Formations of New York State. Non-black shale facies of the upper part of the Union Springs Formation (Stony Hollow and Hurley Members, see Ver Straeten and Brett, 1995; Ver Straeten et al., in prep), where present in New Jersey are generally covered by glacial and fluvial deposits in northwestern New Jersey. However, Yolton (1967) reports the goniatite cephalopod *Agoniatites vanuxemi* from northwestern New Jersey, an index fossil of the Cherry Valley Member, the lowest strata of the Mount Marion Formation in eastern New York.

The fauna of the black shale facies of the Marcellus subgroup is typified by extremely low diversity, diminutive faunas, (the brachiopod *Camarotoechia limitare*, the dacryoconariid *Styliolina fissurella*, the bivalve *Leiopteria laevis*, and nautiloid cephalopods).

Green Pond-Skunnemunk Outlier, Northern New Jersey and Southeastern New York

Connelly Formation. Quartz pebble conglomerate of the Connelly Formation in the Green Pond-Skunnemunk Outlier is the lateral equivalent of the Oriskany and Glenerie Formations along the main Devonian outcrop belt. Herman and Mitchell (1991) report that the Connelly Conglomerate in the outlier appears as thin-bedded, light gray to yellowish gray, and weathers to a grayish orange color. The unit unconformably overlies the Berkshire Valley Formation (Lower Devonian Helderberg Group) in New Jersey.

Boucot (1959) reports five brachiopods (*Costispirifer arenosus, Meristella* sp., *Hipparionyx proximus, Rensselaeria elongata*, and *Beachia* sp.) from the Connelly Formation in the New York part of the Green Pond-Skunnemunk Outlier. These forms are part of the classic fauna of the Oriskany Formation and equivalents across eastern North America.

Esopus Formation. The Esopus Formation of the Green Pond-Skunnemunk Outlier, similar to the main outcrop belt, consists dominantly of dark gray, non-calcareous mudstones and siltstones with a minor amount of fine-grained sandstone. It abruptly overlies the Connelly Conglomerate. The formation has received little attention in New Jersey; however, in the northern part of the outlier (NY), the Esopus Shale has been the focus of several stratigraphic and paleontological studies (Boucot, 1959; Boucot et al., 1970; Marintsch and Finks, 1982).

Boucot et al. (1970) report four members from the Esopus Formation in the Green Pond-Skunnemunk Outlier: 1) a lower light to dark gray siltstone unit with abundant *Zoophycos* traces and a large brachiopod fauna (Mountainville Member); 2) an overlying interval of dark gray to black mudstone with no shelly fauna and a lack of *Zoophycos* traces (Quarry Hill Member); 3) light gray to bluish gray fine sandstones and coarse siltstones, with lenses of abundant shelly fauna and *Zoophycos* (Marintsch and Finks, 1982; Highland Mills Member); and a fourth division of bioturbated (*Zoophycos*-churned) black siltstone and mudstone (Eddyville Member).

The brachiopods and trace fossils of the Esopus Formation in the Green Pond-Skunnemunk Outlier have been discussed in detail by Boucot (1959), Boucot et al. (1970), and Marintsch and Finks (1982); non-brachiopod forms were also noted by Marintsch and Finks (1982). Reported shelly fossils include approximately 30 species of brachiopods (e.g., *Leptocoelia flabellites*, *Platyorthis planoconvexa*, *Acrospirifer murchisoni*, *Anoplia nucleata*, and *Etymothyris* sp.), trilobites (*Synphoria*, a proetid, and dalminitaceans), platyceratid gastropods, minor amounts of pelmatozoan debris, and a small ramose tabulate coral. Sixteen species of ichnofossils were reported by Marintsch and Finks (1982), which include *Zoophycos*, *Skolithos*, *Chondrites*, and *Planolites*. The shelly fossils are dominantly from the Mountainville Member, with a lesser number from the Highland Mills Member; none are reported from the Quarry Hill Member.

Pine Hill Formation. The Pine Hill Formation of Boucot et al. (1970) consists of fossiliferous, slightly calcareous siltstone, sandstone, and conglomerate that overlie the Esopus Formation in the Green Pond-Skunnemunk Outlier. The lower contact is gradational with the Esopus Shale; the upper contact of the formation has not been reported from the outlier. Two members were recognized by Boucot et al. (1970) in southern New York and northern New Jersey: 1) a lower unit of thin- to medium-bedded, light- to medium-gray siltstone and fine sandstone, with abundant brachiopods and bivalves; plant root traces occur interbedded with marine fossils near the top of the strata near Highland Mills (CAV, field notes; Woodbury Creek Member); and 2) fossiliferous quartz pebble conglomerate and quartz-rich sandstone (Kanouse Member).

Diverse brachiopod-dominated faunas characterize the fauna of the Pine Hill Formation in the Green Pond-Skunnemunk Outlier, with bivalves common in the upper part of the Woodbury Creek Member. Boucot (1959) reported 11 brachiopods from the Woodbury Creek Member (e.g., *Amphigenia preparva* and *Etymothyris* sp. (in lower part), *Amphigenia elongata* (in upper part), *Eodevonaria arcuata*, and *Anoplia nucleata*); Boucot (1959) and Boucot et al. (1970) report >20 brachiopods from the overlying Kanouse Member (e.g., *Amphigenia elongata*, *Leptaena rhomboidalis*, *Atrypa reticularis*, *Elita fimbriata*, and *Eodevonaria arcuata*). Kindle and Eidman (1955) also report five corals, four bivalves, two gastropods, two cephalopods, a rostroconch, a tentaculitid, and several trilobites from the Kanouse Member near Highland Mills, N.Y.

The strata of the Esopus and Pine Hill formations in the Green Pond-Skunnemunk Outlier have recently been discussed by Ver Straeten and Brett (1995) who propose that the lower three members of the Esopus Formation in the outlier (Mountainville, Quarry Hill, and Highland Mills Members) represent the lateral equivalent of the three informal members of the main New York outcrop belt. The overlying fourth member of the Esopus (Eddyville Member) and the Woodbury Creek Member of the Pine Hill Formation are the probable equivalents of the three members of the Schoharie Formation in New York (lower and upper units along the main New Jersey outcrop belt). The Kanouse Sandstone is correlative with the lower part of the Onondaga Limestone and Buttermilk Falls Limestones of New York, New Jersey, and Pennsylvania.

Cornwall Formation. The Cornwall Formation of the Green Pond-Skunnemunk Outlier is composed dominantly of black shale-dominated facies of the lower part of the Hamilton Group. As noted above, its basal contact with the underlying Kanouse Member is nowhere exposed in the outlier. The easily erodible black shales are generally covered in the outlier, and are poorly understood. Rickard (1975) correlates the Cornwall Formation with the Bakoven Member of the Union Springs Formation (terminology of Ver Straeten et al., 1994, in prep.); at present none of the associated strata in eastern New York State (Stony Hollow and Hurley Members, Union Springs Formation; Cherry Valley, Berne, and Otsego Members, Mount Marion Formation) have been recognized in the Cornwall or overlying Bellvale Formations in the outlier. Therefore the relationships between the outlier and the main outcrop are at present poorly understood.

Herman and Mitchell report approximately 290 m of Cornwall strata in New Jersey. Fossils of the Cornwall Formation are characteristic of Middle Devonian black shale-dominated facies, and include leiorhynchid brachiopods, other small brachiopods and bivalves, dacryoconariids (e.g., *Styliolina fissurella*), and nautiloid and goniatite cephalopods.

Bellvale Formation. Strata above the Cornwall Formation are represented by silty shales and argillaceous siltstones to sandstones with marine fossils that grade upward into pebbly sandstones with abundant plant material (Sulenski, 1969). The "Bellvale Formation" represents progradation of offshore marine to nearshore and non-marine environments into northern New Jersey and southeastern New York during the Middle Devonian. The contact with the underlying black shale-dominated section is not known, but is presumed gradational. Normal marine faunas in the lower known part of the Bellvale Formation feature classic Middle Devonian Hamilton Group faunas that include the brachiopods *Mucrospirifer mucronatus*, *Tropidoleptus carinatus*, *Devonochonetes coronatus*, and *Spinocyrtia granulosa*, and the bivalve *Grammysia* (Sulenski, 1969). Rickard (1975) correlates the Bellvale Formation as the lateral equivalent of the Union Springs, Mount Marion-Oatka Creek, and Skaneateles Formations of the main outcrop belt of New York. Work by Sulenski (1969) focused dominantly facies and paleoenvironments of the Bellvale and overlying Skunnemunk Formations in the outlier in southeastern New York. Kirby (1981) examined both units in the Green Pond-Skunnemunk Outlier in both New Jersey and New York. Herman and Mitchell (1991) estimate up to 600 m of Bellvale Formation in the New Jersey part of the outlier.

Skunnemunk Formation. Relatively coarse, polymictic conglomerate-rich facies and interbedded greenish-gray to red mudstone facies characterize the highest strata of the Green Pond-Skunnemunk Outlier in New Jersey and New York (Skunnemunk Formation). The Skunnemunk Formation represents proximal non-marine distal to proximal alluvial fan sediments (Sulenski, 1969). Fossils consist of plant material and trace fossils. Herman and Mitchell (1991) report approximately 900 m of the Skunnemunk Conglomerate in northern New Jersey.

DISCUSSION

The Early to Middle Devonian of the Northern and central Appalachian Basin is amongst the best studied in North America. The detailed biostratigraphic work of a host of earlier researchers and observations of the authors will serve to illustrate the concept of "coordinated stasis" and what are termed "ecological-evolutionary subunits," which comprise finer-scale subdivisions of Boucot's (1983) and Sheehan's (1985) "community-evolutionary units." This discussion is based on a survey of major faunal lists of a relatively small number of paleontologists (Grabau, 1906: Goldring, 1935, 1943; Boucot, 1959, pers. commun., 1995; Boucot et al. 1970; Boucot and Rehmer, 1977; Buehler and Tesmer, 1963) to insure consistency in megafossil identification. In addition, most nearly similar facies have been compared so as to minimize facies-related factors as much as possible. In the following section, differences between each of six late Early to Middle Devonian ecological-evolutionary subunits are briefly characterized.

As noted above, the lower Devonian Helderberg Group is terminated by the major Wallbridge Unconformity, although in New Jersey and parts of New York and Pennsylvania the break between underlying and overlying strata is relatively minor to nearly conformable. In many areas, the overlying Oriskany Formation is represented by shoreface to shallow shelf quartz arenites with an assemblage of robust brachiopods. In northwestern New Jersey and southeastern New York, however, Oriskany-equivalent strata are represented by finer-grained, chert-rich carbonates of the Glenerie Formation with a diversity of taxa. This Glenerie-Oriskany fauna is characterized by a diverse assemblage of >94 species. In eastern New York, approximately 25 of these (ca. 25%) are holdovers from the underlying Helderberg Group. The remainder are unique to the Oriskany Formation, which was widespread across eastern North America at that time.

The fauna associated with dark gray shales and siltstones of the Esopus Formation, as noted above, generally consists of low diversity-low abundance assemblages characterized by *Pacificocoelia* brachiopods and the trace fossil *Zoophycos*. The diverse brachiopod-dominated assemblage of the Green Pond-Skunnemunk Outlier, however, shows a remarkable contrast with the underlying and overlying formations.

Of 34 brachiopods reported by Boucot (1959) and Boucot et al. (1970), 29 are exclusive to the Esopus Formation; four are holdovers from the underlying Glenerie-Oriskany fauna and two continue upward into the overlying Schoharie and Onondaga Formations. The distinctiveness of the Esopus fauna may in part be facies related, associated with basin subsidence/transgression and relatively high siliciclastic input. Comparison of the relatively shallower-water Esopus settings of the outlier with relatively deep water Glenerie and Schoharie environments may indicate, however, that the distinctive Esopus fauna is more than facies-dependent.

The calcareous mudstones and argillaceous to silty limestones of the Schoharie Formation display a return to conditions similar to those seen in deeper water settings of the Glenerie Formation and the older Helderberg Group. The Schoharie carries a rich fauna (ca. 125 species) with an abundance of brachiopods, some corals, numerous trilobites, and particularly a diverse fauna of nautiloid cephalopods. This fauna is highly distinctive from that of comparable muddy carbonate facies of the underlying Glenerie assemblage. Only approximately 10 of >94 Glenerie-Oriskany species (10.6%) carry through into the Schoharie Formation, and constitute about 8.1% of the rich Schoharie fauna.

Widespread shallow to deeper shelf facies of the Onondaga Formation feature a highly diverse assemblage of over 200 species, which includes brachiopods, corals, crinoids, gastropods, and other forms. Overall, 37 of these (ca. 12%) are holdovers from the older Schoharie Formation. This percentage is higher for brachiopods; 21 of 32 common Onondaga brachiopods, well over half, are retained from the underlying Schoharie Formation. Within the Onondaga, a majority of the faunal elements (ca. 78%) occur throughout the formation, which may represent approximately 6-7 million years. Only 31 Onondaga species, however, continue through into the overlying Hamilton Group fauna where they constitute a relatively small proportion of that highly diverse fossil assemblage.

Between the classic Onondaga and Hamilton faunas, a distinctive and unique assemblage occurs within the upper part of the Union Springs Formation (Stony Hollow and Hurley Mbrs.) and equivalent strata across eastern North America. This fauna, characterized by the brachiopod *Variatrypa arctica*, is presently under intensive study. Preliminary study by A.J. Boucot and others (pers. commun., 1995) indicates that of over 20 brachiopods, nearly all are exclusive to the Union Springs Formation and its equivalents. Trilobites, corals, and cephalopods of this fauna are also unique to this interval. Much of the fauna migrated into the eastern United States from more equatorward Devonian settings in arctic Canada (Koch, 1988; see Ver Straeten et al., 1994); Boucot (1990) suggests that changes in the global climatic gradient permitted dispersal of warmer water faunas into the Appalachian Basin at that time.

In addition, strata of the upper part of the Union Springs Formation and the lowest strata of the overlying Mount Marion Formation (Marcellus subgroup) are marked by a global extinction-radiation-extinction event, the Kacak-*otomari* bioevent (House, 1985; Truyols-Massoni et al. 1990). This occurrence is marked by widespread changes in pelagic faunas (goniatite cephalopods and dacryoconariids) and is characterized in the Appalachian Basin by a succession of goniatite faunas in the classic cephalopod-rich Cherry Valley Member and underlying strata. This event is essentially synchronous world-wide, and is reported from North America, Europe, North Africa, and China (Chlupac and Kukal, 1986; Truyols-Massoni et al., 1990).

A second major incursion of new taxa into the Appalachian Basin occurs in the lower part of the Mount Marion Formation and equivalent strata across the Appalachian Basin. The first appearance of the Hamilton Group fauna is associated with the migration of a large number of species from the Rhenish-Bohemian region of Europe (Boucot, 1975; Koch, 1978). This changeover also involves the extinction of several long-ranging lineages (e.g., Rensselaeria-Amphigenia brachiopods). Of over 330 species known from the Hamilton Group, only 31 appear to be holdovers from the Onondaga Formation (a majority of which are not found in the intervening Union Springs assemblage). On the other hand, over 80% of these Hamilton forms are known to persist throughout this time (ca. 4-5 million years); fewer than 10 species are known to become extinct in the interval, and very little introduction of new faunal elements occurs.

Each of the six faunas or "ecological-evolutionary units of the Late Early to Middle Devonian Appalachian Basin was relatively stable for up to several million years. During these interludes of stasis bathymetrically-related species associations or biofacies tracked shifting depositional environments. Few species (<10%) were added by speciation or immigration and fewer became extinct. However, during much shorter episodes (ca. 10-100 kyr) major restructuring of all biofacies occurred as many species (lineages) became locally extinct, or evolved rapidly and, in some cases, large numbers of immigrant species became established. Most of these episodes appear to coincide with global bioevents (Boucot, 1990; Brett and Baird, in press). Several of the faunal turnovers (Esopus, Schoharie, Union Springs, and Hamilton assemblages) are associated with major eustatic transgressions and/or tectonic subsidence events. These highstands may have been associated with climatic change, widespread anoxia, and altered migration routes. Major lowstands (e.g., pre-Oriskany, pre-Onondaga may also have caused faunal restructuring events. Hence, the synthesis of detailed stratigraphic and paleontological data may provide significant insights into the dynamics of ecological-evolutionary bio-events in the Appalachian Basin.

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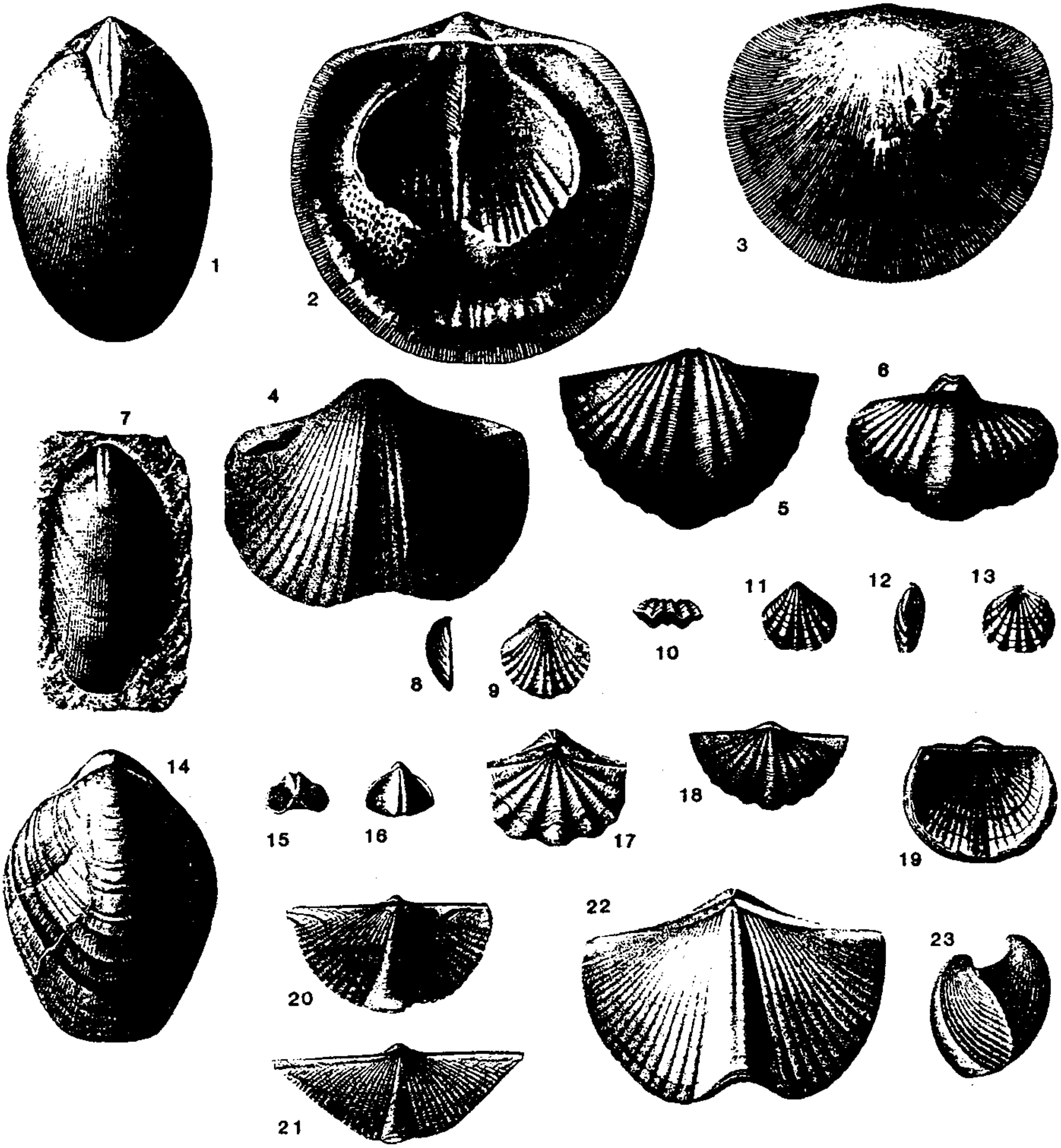

Plate 1. Upper Lower and Middle Devonian brachiopods. 1, *Rensselaeria elongata*; 2-3, *Hipparionyx proximus*; 4, *Costispirifer arenosus*; 5-6, *Acrospirifer murchisoni*; 7, *Etymothyris gaspensis*; 8-9, *Leptocoelia flabellites*; 10-13, *Pacificocoelia acutiplicata*; 14, *Amphigenia elongata*; 15-16, *Pentagonia unisulcata*; 17, *Megakozlowskiella raricosta*; 18, *Acrospirifer duodenaris*; 19, *Tropidoleptus carinatus*; 20-21, *Mucrospirifer mucronatus*; 22-23, *Spinocyrtia granulosa*. Numbers 1-6, Oriskany-Glenerie Fms.; 7, Esopus Fm.; 8-9, Oriskany and Esopus Fms.; 10-13, Oriskany to Union Springs Fms.; 15-18, Onondaga Fm.; 19-23, Bellvale Fm.

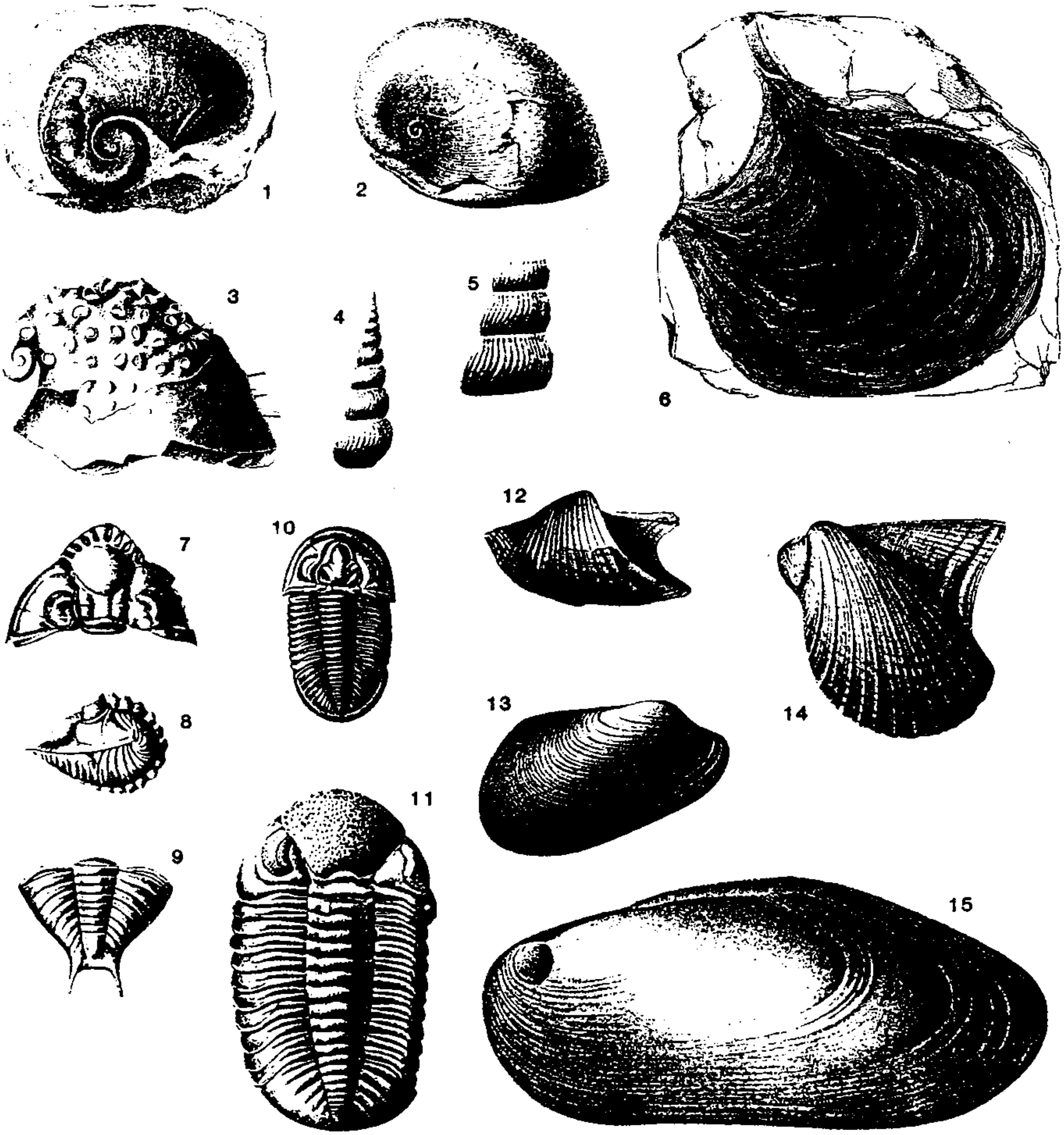

Plate 2. Additional Upper Lower and Middle Devonian Fossils. 1, *Platystoma gebhardi* (gastropod); 2, *Platystoma ventricosa* (gastropod); 3, *Platyceras dumosum* (gastropod); 4-5, *Paleozygopleura hamiltonensis* (gastropod); 6, *Zoophycos* (trace fossil); 7-9, *Odontocephalus selenurus* (trilobite); 10, *Dechenella haldemani* (trilobite); 11, *Phacops rana* (trilobite); 12, *Hippocardia cuneus* (rostroconch); 13, *Modiomorpha mytiloides* (marine bivalve); 14, *Cornellites fasciculata* (marine bivalve); 15, *Archanodon catskillensis* (freshwater bivalve). Numbers 1-2, Oriskany-Glenerie Fms.; 6, Esopus to Bellvale Fms.; 12, Schoharie to Bellvale Fms.; 3, 4-5,7-9, Onondaga Fm.; 10, Union Springs Fm.; 11, 13-14, Bellvale Fm.; 15, Bellvale and Skunnemunk Fms.

GRAPTOLITE BIOSTRATIGRAPHY AT THE JUTLAND KLIPPE, NEW JERSEY

David C. Parris, Louise F. Miller, and Stanley C. Finney

ABSTRACT

The Jutland sequence of Hunterdon County has produced substantial graptolite faunas during many years of geologic studies. List of taxa are reviewed herein, with new information on work in progress. The Clinton Block and Supply Site has produced three (possibly four) sequential faunas. Preliminary identification lists suggest that they are in an order to establish that the Jutland sequence is not overturned.

INTRODUCTION

For nearly a century the Ordovician rocks near Jutland, Hunterdon County, New Jersey have commanded particular interest (Figure 1). Weller (1903) noted the presence of graptolites there in fair abundance, in contrast with other rocks of the Ordovician System in New Jersey. Commenting on the unusually complicated structure, Weller's report foreshadowed other efforts to interpret the area, which mostly lies within the Township of Union. Efforts were made to obtain precise dates, decipher the complex structural deformation, and to broaden interpretations for a better understanding of the Taconic Orogeny, (Dodge, 1952; Perissoratis *et al*, 1979; Markewicz, 1984, Parris and Cruikshank, 1986). Although its area is small, the Jutland Sequence (often called the Jutland Klippe) has broader implications for interpretation of Taconic area movements. None of these previous efforts has satisfactorily interpreted this tract, nor can that be done in this brief space. However, the biostratigraphic evidence of the graptolite facies can be reasonably reviewed based on new discoveries and re-examination of materials previously assembled. Some new faunal information, previously unpublished, is presented here.

NEW SITE INFORMATION

The Clinton Block and Supply site in Union Township (Figure 2) is a major source of new information on the Jutland Sequence. Although much remains to be learned by careful study of the quarry areas, at least four graptolite-bearing levels have thus far been collected. A significant amount of deformation is present at the site, but at least three of these collections are in an apparent sequence, numbered herein as Collections 19-21. The collection numbered 22 is possibly in sequence as well, probably overlying the other three, but this remains to be fully investigated. The units generally strike N55° and dip 24°S, in apparent consistency with collection 19 lowest, collection 20 intermediate, and collection 21 highest. The latter is from a bentonite high in the quarry face.

FAUNAL COLLECTIONS

We list here the faunal collections cited by Perissoratis et al. (1979) with minor changes in formal taxonomy and with commentary on sources and repositories. To that list are appended the assemblages collected since that date, noting sources and repositories. Zonation numbers are those of Berry (1960, 1968).

Locality Number	Taxon	Graptolite Zone
1	*Adelograptus lapworthi* (Ruedemann)	2-4
	Adelograptus sp., cf. *A. pusillus* (Ruedemann)	
	Callograptus sp., cf. *C. salteri* (Hall)	
	Clonograptus sp.	
	Dictyonema, cf. *D. quadrangulare* (Hall)	
	Tetragraptus sp. cf. *T. quadribrachiatus* (Hall)	
2	*Adelograptus lapworthi* (Ruedemann)	2-4
	Tetragraptus sp., cf. *T. quadribrachiatus* (Hall)	
3	*Cryptograptus antennarius* (Hall)	probably 9
	Didymograptus sp. cf. *D. nicholsoni* (Lapworth)	
	Glossograptus sp., cf. *G. hystrix* **Ruedemann**	
4	*Cryptograptus antennarius* (Hall)	probably 9
	Dichograptidae	
5	*Climacograptus phyllophorus* Gurley	11-12
	Dicranograptus ramosus (Hall)	
	Nemagraptus sp.	
	Reteograptus geinitzianus Hall	

Locality Number	Taxon	Graptolite Zone
6	*Pseudoclimacograptus scharenbergi* (Lapworth)	11
	Diplograptus angustifolius Hall	
	Dicellograptus, cf. *D. divaricatus* (Hall)	
	Dicellograptus sextans (Hall)	
	Dicellograptus smithi Ruedemann	
	Dicranograptus sp.	
	Glyptograptus sp.	
	Pseudoclimacograptus scharenbergi, cf. var. *stenostoma* (Bulman)	
7	*Pseudoclimacograptus scharenbergi*, cf. var. *stenostoma* (Bulman)	11
	Climacograptus cf. *C. riddelensis* Harris	
	Cryptograptus tricornis (Carruthers)	
	Glyptograptus sp.	
	Orthograptus sp.	
	Retiograptus sp.	
8	*Climacograptus bicornis* (Hall)?	12
	Pseudoclimacograptus scharenbergi cf. var. *stenostoma* (Bulman)	
	Glyptograptus sp.	
9	*Amplexograptus arctus* (Elles and Wood)	probably 10
	Climacograptus sp. cf. C. *riddelensis* Harris	
	Diplograptus sp.	
	Glyptograptus sp.	
	Pseudoclimacograptus sp.	

Locality Number	Taxon	Graptolite Zone
10	*Climacograptus bicornis* (Hall)	probably 12
	Cryptograptus tricornis (Carruthers)	
	Glyptograptus sp.	
11	*Climacograptus riddelensis* Harris	10
	Cryptograptus tricornis (Carruthers)	
	Diplograptus decoratus	
	Glyptograptus cf. *G. teretiusculus* (Hisinger)	
12&13	*Amplexograptus* sp.	probably 10
	Cryptograptus tricornis (Carruthers)	
	Diplograptus? sp.	
	Glyptograptus sp.	
	Hallograptus? sp.	
	Pseudoclimacograptus sp.	
14	*Climacograptus* sp.	11-12
15	*Dicellograptus* sp., cf. *D. nicholsoni planus* Elles and Wood	4-8
16	*Dicellograptus* sp.	11-12
	Pseudoclimacograptus scharenbergi (Lapworth)	
17	*Pseudoclimacograptus modestus* (Ruedemann)	
	Dicellograptus divaricatus salopiensis Elles and Wood	

Locality Number	Taxon	Graptolite Zone
	Dicellograptus sp.	
	Dicranograptus sp.	
	Didymograptus? sp.	
	Climacograptus sp.	
	Glyptograptus? sp.	
18	*Didymograptus sagitticaulis* Gurley	11
	Didymograptus sp.	
	Dicellograptus sp.	
	Dicranograptus cf. *kirki* Ruedemann	
	Dicranograptus ramosus (Hall)	
	Dicranograptus sp.	
	Glossograptus ciliatus Emmons	
	Climacograptus sp.	
	Pseudoclimacograptus sp.	
19	*Isograptus forcipiformis* (Ruedemann)	
	Didymograptus sp.	8-9
	Tetragraptus sp.	
	Xiphograptus? sp.	
	Isograptus victoriae? (Harris)?	
20	*Isograptus* sp.	9
	Glossograptus hystrix Ruedemann	
21	*Glyptograptus* cf. *teretiusculus* (Hissinger)	10
22	*Hallograptus*?	11
	Dicellograptus?	
	Nemagraptus?	

Locality Number	Taxon	Graptolite Zone
	Glyptograptus?	
	Climacograptus sp.	
	Didymograptus sp.	
	Glossograptus sp.	
	Cryptograptus sp.	
	Pseudoclimacograptus sp.	

Localities 1-16 are those cited by Perissoratis *et al.*, (1979) and shown on the map published by them. Localities 1-4 apparently were those of Dodge (1952) although numbered differently therein. Locality 5 was first located by Weller (1903) and Locality 6 was Kummel's locality cited by Ruedemann (1947).

Locality 17 has not been published previously. As with several older discoveries, it is along the Lehigh Valley Railroad tracks east of Jutland, in this case approximately one kilometer. The graptolites were collected by Richard Volkert and identified by Claire Carter.

Locality 18 was published by Parris and Cruikshank (1986). Localities 19-22 all are from the Clinton Block and Supply Site, as noted above. As of this writing identifications of the taxa from these localities are preliminary, with complete faunal lists in preparation.

Locality 1 of Perissoratis *et al*. (1979), which was also Locality 1 of Dodge (1952), is now very poorly exposed. In view of its importance as one of the oldest sites (Zones 2-4), we have made an especially strong effort to obtain material from there. The site, generally known as Hedgehaven Farm, has now yielded additional specimens of graptolitic (generally dendroid) and conodont faunal material (NJSM 16566 and NJSM 16131). Our preliminary identifications confirm previous age determinations for the site. To date we have been unable to locate the repository of Dodge's original specimens, although there is no doubt that they were competently studied and very well illustrated (Dodge, 1952).

Materials that were part of the basis of the age determination for Locality 6 are on deposit at the New Jersey State Museum (NJSM8132, 10914-10920). The specimens from Locality 17 are NJSM 12725. Specimens from Locality 18 were cited by number previously (Parris and Cruikshank, 1986). We have collected material from Locality 16 which has added *Pseudoclimagraptus scharenbergi* to that faunal list.

Numbers currently assigned to specimens from the Clinton Block and Supply Site are as follows: NJSM 16481-16490 from Locality 19; NJSM 16564 for Locality 20; NJSM 16565 for Locality 21. Specimens from Locality 22 are New Jersey Geological Survey specimens, currently unnumbered, but under study at the New Jersey State Museum.

DISCUSSION

Any structural interpretation of the Jutland Sequence must be based on evidence from multiple sources and analyses, of which the graptolite biostratigraphy is but one aspect. However, the structural interpretation of Perissoratis et al (1979) antedates the majority of discoveries at the Clinton Block and Supply site and the faunal evidence from that site does not support their interpretation, that is, that the sequence is overturned. No previous faunal collections from the Jutland sequence could be compared directly in continuous exposures with measureable sections. The Clinton Block and Supply Site has produced three and possibly four faunal levels in sequence represented by collections 18-21, which are demonstrably older basal faunas to younger upper faunas. There is no reason to suppose that this differs from the Jutland Sequence as a whole, which thus appears to be an original sequence, not overturned. A new structural interpretation will be expected once other investigations are completed.

ACKNOWLEDGEMENTS

We thank the authorities at the New Jersey Geological Survey for their continued cooperation and encouragement, notably Richard Dalton, Donald Monteverde, and Richard Volkert. The extensive field studies of Frank Markewicz were the basis of much of our investigations. The help and permission granted by the Clinton Block and Supply Company was essential to our effort.

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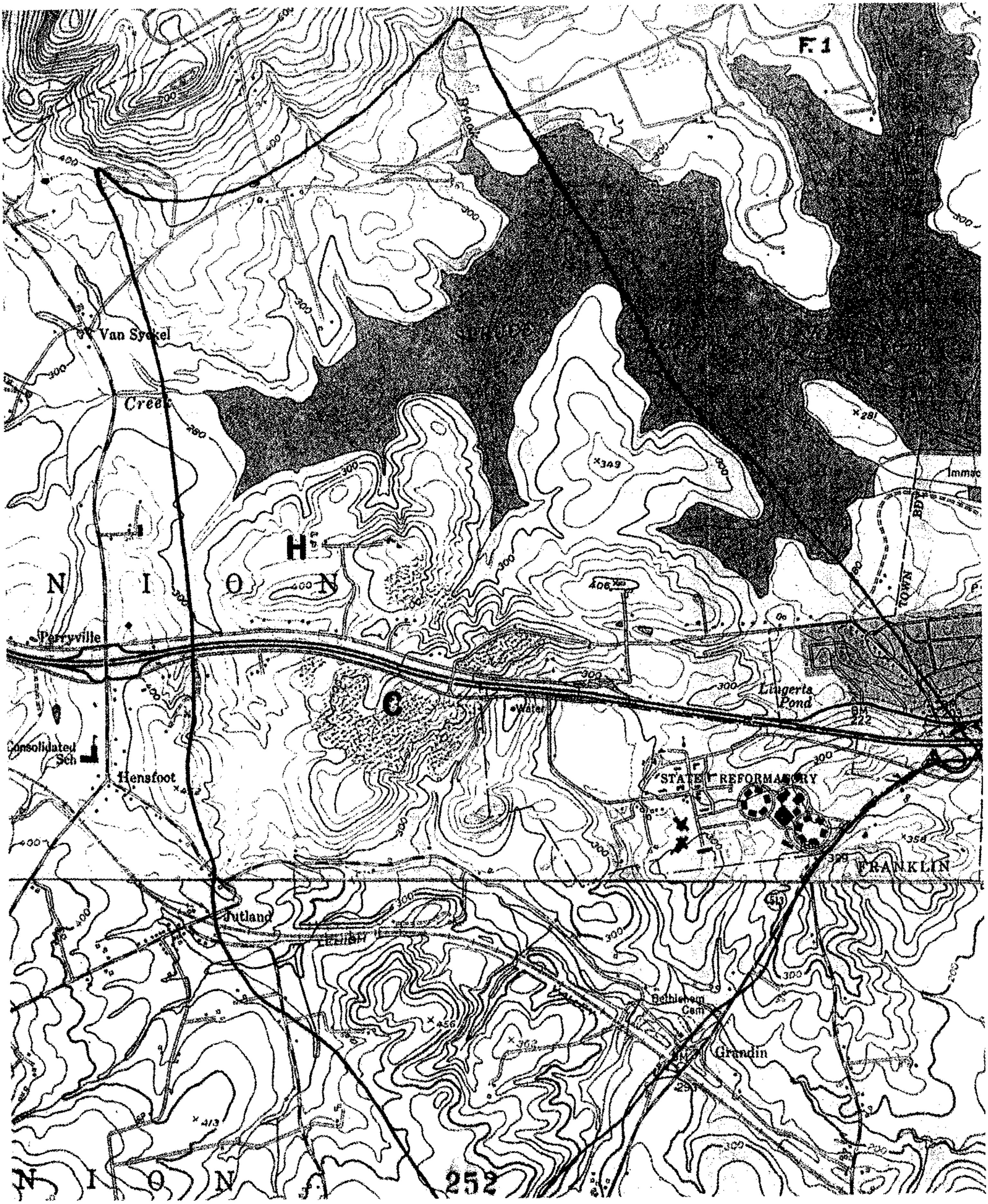
FIGURE CAPTIONS

Figure 1 Approximate area of Jutland sequence rocks (Ordovician Age) in Hunterdon County, New Jersey. Base maps are U.S.G.S. 7 1/2' Quadrangles, portions of High Bridge and Pittstown Quadrangles. Hedgehaven Farm indicated by H; Clinton Block and Supply Site indicated by C.

Figure 2 View toward quarry face at Clinton Block and Supply Site, facing southeast. Photograph taken at level of fauna 20. Fauna 21 is from light banded level (bentonite) high on quarry. Human figure for scale.


F. 1
Van Syckel
Creek
H
N I O N
Perryville
Consolidated Sch
Hensfoot
G
Water
Lingerts Pond
BM 222
STATE REFORMATORY
FRANKLIN
Jutland
Bethlehem Cem
Grandin
×349
×281
×456
×413
×303
×358
406
TOWN
Immac
N I O N
252

Miocene Land Mammals from the Kirkwood Formation of Monmouth County, N.J.

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Abstract: New discoveries of Miocene land mammal specimens from the Asbury Park Member of the Miocene Kirkwood Formation are noted and nineteenth century discoveries are reviewed. The land mammal fossils are mostly teeth which were deposited in an estuarine environment along with remains of sharks, teleosts, turtles, crocodiles, birds, and cetaceans. The land mammal specimens are a time-averaged and transported assemblage that contains both late Arikareean and early Hemingfordian elements.

Introduction

In the nineteenth century, Joseph Leidy and O. C. Marsh obtained fossil land mammal teeth from the marl pits in the Tertiary outcrop belt of the Atlantic coastal plain. Marsh (1893) called the unit that yielded these specimens the *Ammodon* beds, after the most prominent land mammal tooth found in the layer; today this stratum is known as the Asbury Park Member of the Kirkwood Formation (see figure 1). Later, Wood et al. (1941) designated the fossils found in the Kirkwood of Monmouth County as the Squankum Local Fauna. In recent decades amateur collectors have made sporadic new discoveries in the Asbury Park Member in the same area that yielded the original specimens, along the banks of the Manasquan and Shark Rivers. Some of these specimens have been reported elsewhere, but the entire fauna has not been recently reviewed. We report here for the first time some of the newer discoveries and discuss the entire assemblage in a biostratigraphic and paleoecological perspective.

Geology and Stratigraphy

The outer coastal plain region of New Jersey is underlain by largely unconsolidated deposits of Tertiary and Quaternary age. Traditionally the Miocene outcrop belt has been divided into two formations, the Kirkwood and the Cohansey. Unconformably underlying the Kirkwood Formation are two Eocene units, the Manasquan and the Shark River Formations which may actually have a facies relationship.

Overlying the Kirkwood is the widespread Cohansey Formation, the principal substrate of the Pinelands area. Capping the higher hills are the yellow gravels now variously assigned to the Pleistocene, Pliocene, or even in part the uppermost Miocene (Newell et al., 1988). The Kirkwood and the Cohansey can be regarded as a transgressive-regressive sequence, a local representation of the well-documented mid-Miocene transgression. The Kirkwood is subdivided into the Asbury Park, Grenloch and Alloway Clay Members (Isphording and Lodding, 1969). The Asbury Park Member is restricted to Monmouth County, and consists of silty clays that are thought to have been deposited in an estuarine or lagoonal setting; it is usually overlain by the Grenloch Member. This member occupies all of the Kirkwood section in the central part of the outcrop belt; the Grenloch Member is composed of sands and variegated clays. In places in Camden and Gloucester Counties this unit contains large petrified cypress logs, attesting to its fluvial origin. In the southern portion of the outcrop belt the Kirkwood changes facies again, and in Salem and Cumberland Counties it is a dark sandy clay (the Alloway Clay Member) that was mined for marl as recently the 1920's (Richards and Harbison, 1942). The marine origin of this member is suggested by the shellbed in the upper part of the Shiloh marl, which has yielded a fauna of mollusks, sharks and cetaceans.

The Kirkwood Formation has usually been correlated with the Calvert Formation of the Chesapeake Group, and further to the south with the Pungo River Formation in Virginia and North Carolina (Gernant et al., 1971). The Calvert is generally regarded as late Early to mid-Middle Miocene, 20 million to 13 million years old (Vogt and Eschelman, 1987). It contains a fully marine fauna of mollusks, chondrichthyans and cetaceans, but it is probably the most productive unit of the three Chesapeake Group formations for Miocene land mammals (Gernant et al., 1971).

Terrestrial Mammal Fauna

The land mammal fauna of the Asbury Park Member is represented mostly by teeth, which are sufficiently diagnostic in mammals to provide specific taxonomic assignment and biostratigraphic correlation. The first specimens described were peccary and entelodont teeth (Leidy, 1868; Marsh, mentioned in Cope, 1868). Marsh (1871) obtained two tapir teeth from the Shiloh marls of Cumberland County, the only land mammal specimens known from this more marine facies. Marsh also described Rhinoceros matutinus from the Shark River deposits in 1870.

More recently, amateur fossil collectors working the Shark River and Manasquan River exposures have added to this fauna. Among the collectors who have contributed to our knowledge of New Jersey's Miocene land mammals are John Brzostoski, William Novak, Daniel Romeo, Ralph Johnson, and Daniel Kuehne. Additions to the land fauna include the teeth of protoceratids, a horse tooth, a canid tooth, and additional records of rhinoceros, entelodont, and peccaries. This material (or casts of it) resides in several repositories, chief among which are the New Jersey State Museum (NJSM), the Academy of Natural Sciences of Philadelphia (ANSP), the American Museum of Natural History (AMNH), and the Yale Peabody Museum (YPM). See Table 1 for a listing of Miocene land mammal specimens from New Jersey.

The entelodonts were large relatives of the pigs, but with a snout like a wart hog. They must have presented a fearsome appearance. There is some speculation that they may have been carnivorous; Cope (1868) described them colorfully as devouring "the dead bodies of stranded cetacea" and delighting "in swamps and mud." The New Jersey taxon was originally called Elotherium leidyanum by Marsh (1870), but the name was changed to Ammodon (Marsh, 1893), which was subsequently synonymized with Daeodon.

Protoceratids were deer-like artiodactyls with unusual combinations of nasal and brow horns. The genus Prosynthetoceras, to which the New Jersey teeth are attributed (Patton and Taylor, 1971), is well-known from complete skeletons found in Miocene deposits in the American West. Of these, the New Jersey specimens are closest to P. texanus, found in the Garvin Gully fauna of eastern Texas.

Rhinoceros matutinus has been reassigned as Diceratherium matutinum, a Miocene rhino with paired nasal horns. It was a more gracile form than the modern rhinoceras, and may have been more adapted to a semi-aquatic way of life.

The single known horse tooth belongs to the genus Anchitherium. This Miocene horse was a three-toed animal with low-crowned teeth, probably adapted for browsing rather than grazing. Of these horses, it is similar to A. clarenci or A. chico.

The Miocene peccaries were first reported from Calvert Cliffs by E.D. Cope (1867) who described a peccary canine tooth as a cetacean tooth, giving it the misleading name of Cynorca. Recent work by Wright and Eschelman (1987) has demonstrated the existence of several species of peccaries in the Calvert and Choptank Formations of the Chesapeake Group in Maryland. Born in confusion and perhaps misapplied at times to some of the New Jersey Miocene specimens, the peccaries sometimes called "Cynorca" from the Asbury Park Member are identified as Hesperhys in the AMNH collection.

The single known canid tooth is perhaps from a Miocene "wolf", although its stout aspect may not rule out other possibilities such the amphicyonid clade. Another small tooth from the private collection of D. Romeo could be a small carnivore, maybe a mustelid.

Associated Fauna

The most abundant vertebrate remains in the Asbury Park Member are sharks' teeth of typical Miocene genera such as *Odontaspis*, *Isurus*, *Hemipristis*, *Carcharias*, and *Galeocerdo*. Teleost fish spines and scales are present, including a specimen of the basal portion of a catfish spine (M.R. 5 in the Romeo Collection). A turtle (*Testudo trionythus*; see Miller, 1956) and a few small crocodile teeth represent the reptiles, while a single known bird phalanx seems to be from a shorebird.

Cetacean remains are common and include teeth, a jaw section, an auditory bulla, ribs and vertebrae. Most of these are of a size consistent with the delphinids, but since squalodonts such as *Squalodon atlantica* are present some of this material may pertain to these early odontocetes. Certainly there are *Squalodon* teeth found in the New Jersey deposits, and Miocene whales were smaller than many of today's leviathans.

Conclusions: Taphonomy, Paleoecology, Biostratigraphic Correlations

The Asbury Park Member has been considered an estuarine or lagoonal deposit on sedimentological grounds (Isphording and Lodding, 1969). The admixture of marine and terrestrial faunas supports this view, and is corroborated by the nature of the land mammal remains, which consist mostly of resistant elements such as teeth that would withstand prolonged transport. Other localities in the coastal plain demonstrate this same pattern, and we have generalized elsewhere about the nature of these mixed assemblages (Gallagher, Parris, and Spamer, 1986; Gallagher, 1993).

In terms of paleoecology, the fauna is typical of the channel faunas associated with fluvial deposits in the Western deposits of comparable age (Scott, Jepsen and Wood, 1941). One additional indicator of local environments is the paleobotanical evidence; the Asbury Park Member also produces seeds of mangrove trees, which today are commonly found lining estuarine channels in tropical and subtropical coastal environments. So we can build a scenario involving the transport of more resistant channel fauna remains into subtropical estuaries, perhaps by peak-flow conditions such as storms, where the land mammal remains are mixed with more marine forms such as cetaceans and sharks.

In terms of biostratigraphic correlations, the land mammals are somewhat equivocal. Some (such as the entelodonts and the horse) suggest an Arikareean land mammal age (Wood et al., 1941), while other specimens (the protoceratid teeth) are more indicative of a Hemingfordian age (Patton and Taylor, 1971). It is possible that the fauna is a time-averaged late Arikareean to early Hemingfordian taphocoenosis, since the taphonomic evidence indicates that the teeth were probably transported into the depositional environment from a fluvial system which may have sampled bank-stored remains and recycled these specimens downstream during high-erosion events.

The fauna itself is characteristic of a widespread early to middle Miocene land mammal assemblage that is found in the Miocene deposits of Gays Head on Martha's Vineyard (Kaye, 1983), the Smyrna Local Fauna of Delaware (Ramsey et al., 1991), the lower part of the Calvert Formation in Maryland and in lower units of the Miocene elsewhere further south in the Atlantic Coastal Plain. Farther afield, it seems to be correlative to the Gulf Coast Garvin Gulley Local Fauna of Texas and to the Miocene assemblages found in the deposits of the northern Great Plains.

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We would like to thank the collectors who have been generous in donating and loaning specimens from the Miocene sites, including John Brzostoski, Ralph Johnson, Daniel Kuehne, William Novak and Dan Romeo. For access to specimens in their care we thank Robert Evander and John Alexander of AMNH. Ted Daeschler of the Academy of Natural Sciences provided us with useful discussions of the fauna and access to casts in the ANSP collections.

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Table 1- List of Miocene Mammal specimens from New Jersey

Taxon, element	NJSM	ANSP	AMNH	YPM	Private
Diceratherium matutinum lower rt M3 + astragulus	12130 (cast)		38950 (cast)	11873 (type)	
Rhinoceros indet.- fragment of premolar	16308				Gilmore
Diceratherium cooki lower molar	unnumb.	19545 (cast)			
Diceratherium sp. upper molar	16221 (cast)	18988 (cast)			Romeo
Diceratherium armatum? fragment of molar			14645		
Diceratherium sp? left M1 or M2 (fragment)			48980		Johnson
Diceratherium armatum molar fragment			14645		
Ammodon leidyanus left P4 left M3	11231 casts		38951 casts	12040 12041	
cf. *Ammodon* premolar fragment	16307				
cf. *Ammodon* molar M3	16222 cast	18989 cast			Romeo
Entelodont deciduous canine			48981 cast		Johnson
Daeodon (*Ammodon*) leidyanum premolar fragment	16560 cast		94462 cast		Novak
Daeodon leidyanum left I3			104644 cast		Johnson
Prosynthetoceras cf texanus- right M3	16304 16305		88178 cast		Brzostoski
cf. *Prosynthetoceras* tooth cusp	11873				
cf. *Cynorca*-left m3	15477				
Hesperhys antiquus left M1, type, left M3			38953- 38955		
Anchitherium sp. M3	16559 cast		94463 cast		Novak
Tapirus validus (Shiloh) left P3 and P4			15592 casts		
Tapirus validus (Shiloh) M3				13474	
indet. mammal incisor	16306				
canidae indet. right P4		19352 cast			Romeo
indet. mammal tooth loph	16563 cast				Novak

Figure 1- Stratigraphic section at Shark River site, west of Garden State Parkway, Tinton Falls, Monmouth County, N.J. Measurements on left of column in feet (Additional data courtesy of D. Clements).

A. Topsoil (Lakewood Sand)

B. Clayey, silt, brownish black (5YR 2/1), micaceous, organic, slightly glauconitic, fine laminations of gray (5YR 4/1) fine quartz sand. Top of Asbury Park Member.

C. Medium to coarse sand, dark gray (5YR 4/1).

D. Clayey silt, brownish black (5YR 2/1), micaceous, organic, slightly glauconitic, fine laminations of gray (5YR 4/1) quartz sand.

E. Medium to coarse sand, dark gray (5Y 4/1), glauconitic, small phosphate pebbles, fossiliferous. Bottom of Asbury Park Member.

F. Medium to coarse sand, greenish gray (5GY 6/1) creamy, mottled, indurated, argillaceous, glauconitic, fossiliferous. Squankum Member of the Shark River Formation.

Figure 1

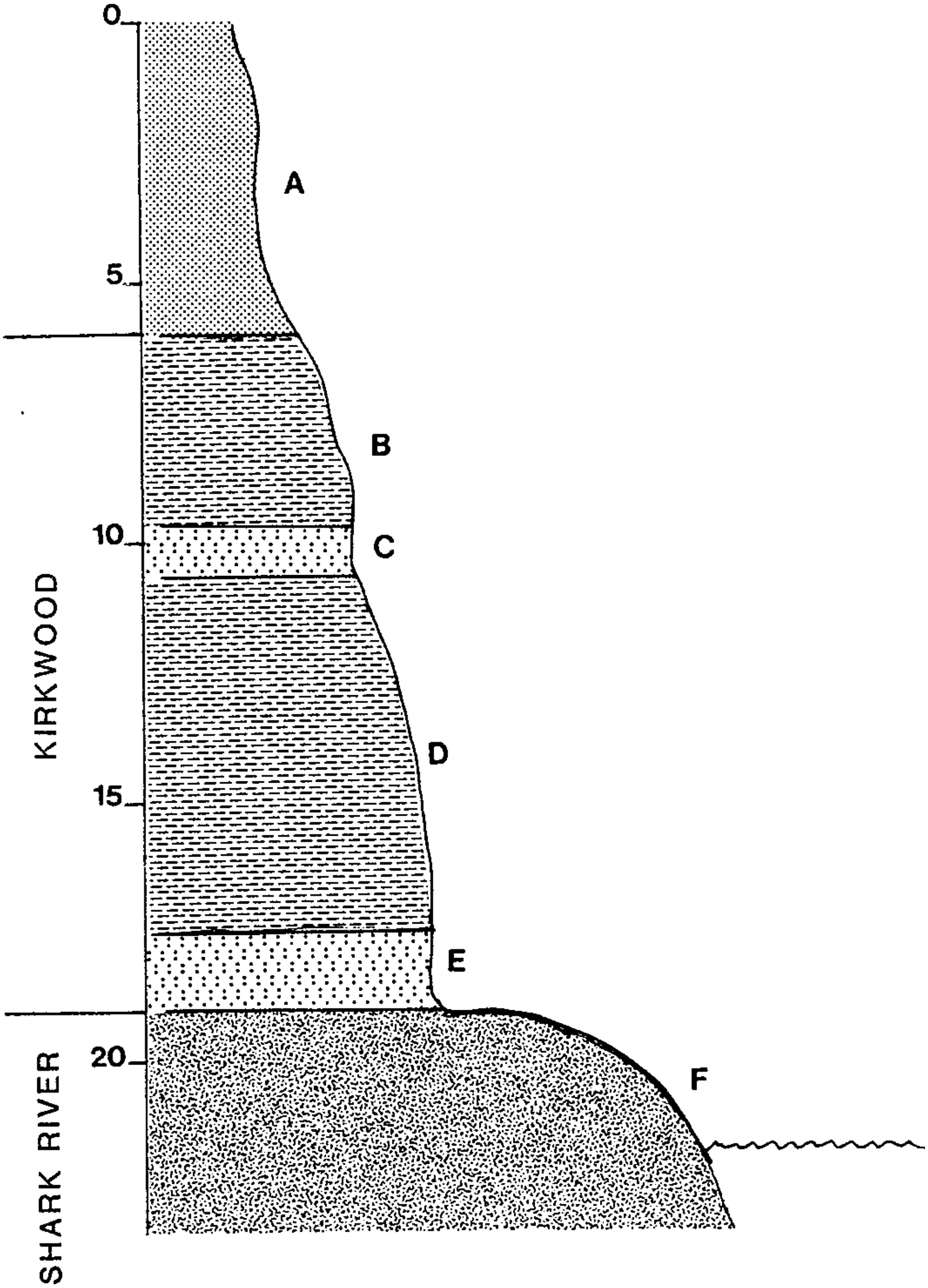


Figure 2- Miocene mammals from the Asbury Park Member, Kirkwood Formation, Monmouth County, New Jersey. All specimens with centimeter scale.

A. *Diceratherium cooki*- lower molar from Manasquan River; collected by E. Gilmore. Oblique occlusal view.

B. *Diceratherium matutinum*- upper molar from Shark River; collected by D. Romeo. Occlusal view.

C. *Daeodon* (*Ammodon*) *leidyanus*- lower molar from Shark River; collected by D. Romeo. Occlusal view.

D. Entelodont - deciduous(?) canine from Shark River; collected by R. Johnson. Labial view of AMNH cast.

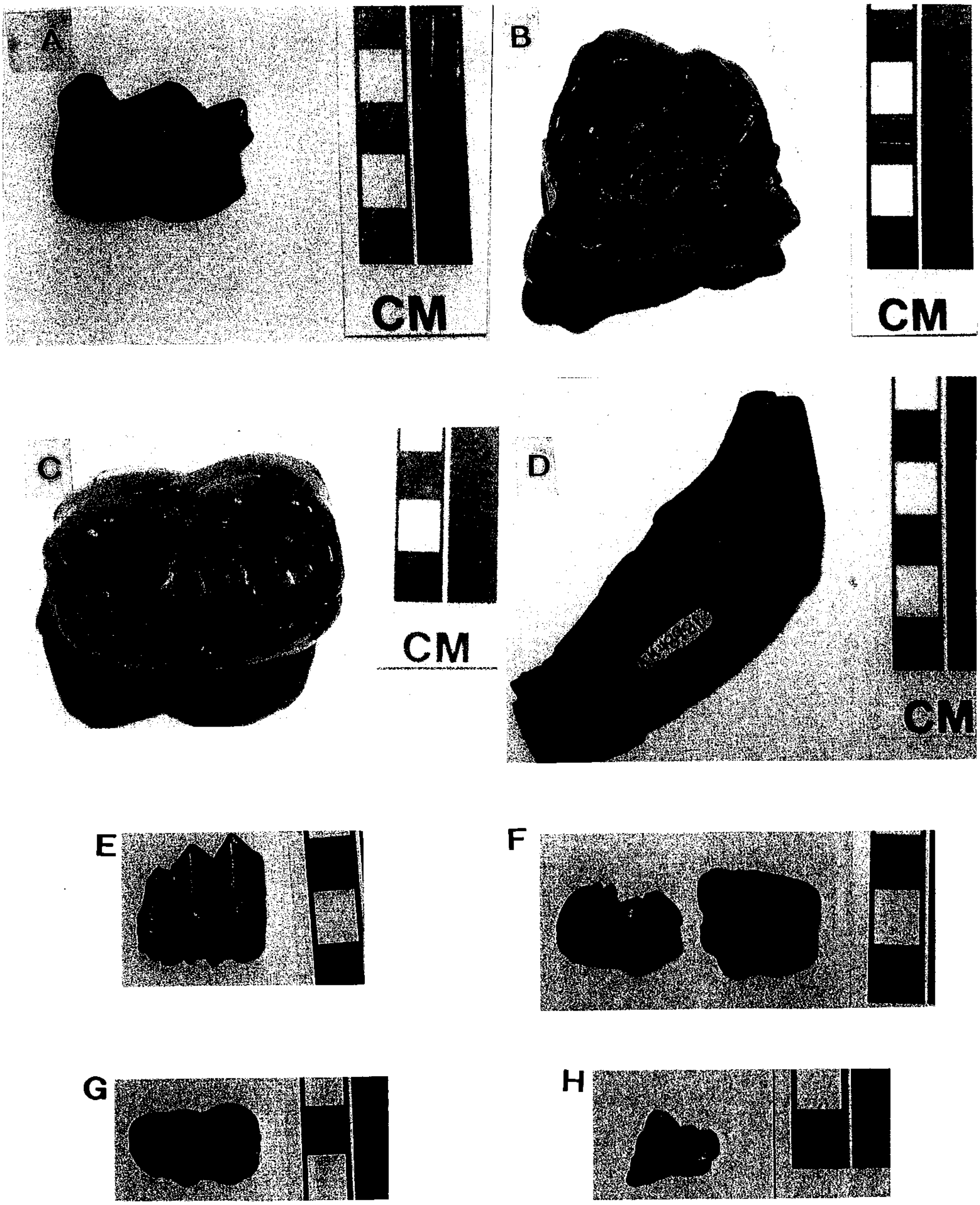
E. *Prosynthetoceras* cf. *texanus*- right lower molar from Shark River; collected by J. Brzostoski. Labial view.

F. *Anchitherium* sp.- right upper molar from Shark River; collected by W. Novak. Anterior view (left) and occlusal view (right) of AMNH cast.

G. "*Cynorca*" (=*Hesperhys*?)- lower left molar from Manasquan River; collected by D. Kuehne. Occlusal view.

H. Canid indet.- right lower premolar from Shark River; collected by D. Romeo. Oblique occlusal view.

Figure 2



Palynologic and climatic records, New Jersey Coastal Plain: Evidence for late early Miocene climatic transition

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ABSTRACT

We interpret paleoclimates from pollen assemblages found in lower to middle Miocene sequences calibrated to the Geomagnetic Polarity Timescale (GPTS) with Sr-isotopic stratigraphy from New Jersey Coastal Plain coreholes. In the lower Miocene (~22-20) Kirkwood 1a and 1b sequences (Kirkwood and Shiloh Marl Formations), the predominance of *Quercus, Pinus, Carya,* along with minor amounts of subtropical to tropical exotics, indicates warm temperate climatic conditions prevailed during deposition of this interval. A minor cooling event at 20.6 Ma ± 0.4 m.y. is inferred from the presence of *Picea, Tsuga,* and *Alnus.* A 2 m.y. hiatus (~20.2-18.1 Ma) between the Kirkwood 1b (Shiloh Marl Formation) and Kirkwood 2a (Wildwood Formation) excludes paleoclimatic interpretation from this interval. The Kirkwood 2a sequence (18.1-17 Ma) records a paleoclimatic transition from warm temperate to subtropical in the lowermost beds, temperate in the lower beds, and cool to cold temperate in the middle to upper beds. The climatic transition (cooling) begins at ~17.8 Ma ± 0.4 m.y., and is reflected in a dominant *Quercus, Carya, Picea* assemblage, along with lesser percentages of *Tsuga* and *Alnus*; exotics are rare or absent from this interval. A long hiatus of ~2-3 m.y. separates the Kirkwood 2b (Wildwood Formation) and Kirkwood 3 (Belleplain Formation) sequences. The base of the Kirkwood 3 sequence at the 150X-Atlantic City corehole (Sr-isotopic age of 13.6 Ma), contains a warm temperate to subtropical pollen assemblage, with intervals of cool to cold temperate paleoclimates higher in the section. Timing of climatic trends in the Kirkwood 3 sequence is more difficult to discern due to lower resolution (± 0.9 m.y.) from Sr-isotope stratigraphy in the middle Miocene.

INTRODUCTION

The stratigraphic framework of the lower to middle Miocene Kirkwood Formation has been greatly improved by continuous-corehole drilling in the New Jersey Coastal Plain (Owens et al., 1988; Miller et al., 1994, in press), integration of the East Coast Diatom Zones of Andrews (1987, 1988), and application of Sr-isotope stratigraphy (Sugarman et al., 1993) allowing correlation of shallow marine strata to the Geomagnetic Polarity Timescale (GPTS). Subsequent drilling of the Belleplain State Forest corehole in 1991 (Fig. 1), the recent 150X-coreholes at Island Beach, Atlantic City, and Cape May (Miller et al., 1994; in press; Miller and Sugarman, 1995), and reexamination of existing cable tool wells such as Wildwood 198A (Woolman, 1895) and split spoon wells for the new geologic map of New Jersey (Owens et al., 1995a, 1995b) have further clarified and redefined the stratigraphy of the Kirkwood Formation.

Sr-isotope stratigraphy is increasingly being used as a method for chronostratigraphy, especially in shallow marine strata which contain limited calcareous material, or lack suitable index taxa for calibrations with more precisely dated pelagic sections. (For an introduction and review of Sr-isotope stratigraphy see Elderfield, 1986). For the early Miocene (~23-16 Ma), resolution of ±0.4 m.y. can be achieved , whereas for the middle Miocene (~15-9 Ma), resolution decreases to approximately ±0.9 m.y. because of a lower $^{87}Sr/^{86}Sr$ rate of change (Oslick et al., 1994). With Sr-isotope age estimates for the Kirkwood sequences ranging from 24-11 Ma (lower to middle Miocene; Sugarman et al., 1993; Miller et al., 1994; Miller and Sugarman, 1995), Sr-isotope stratigraphy provides: 1) an excellent high resolution tool to date carbonate fossil material; 2) calibrate sequences to the GPTS for stratigraphic modeling and global correlations; and 3) provide age estimates for the range of contained biota and biozones.

Sr-isotope stratigraphy also enables us to improve our understanding of paleoclimates during the lower to middle Miocene based on pollen assemblages preserved in New Jersey Coastal Plain sediments. The Eocene-Oligocene transition marks a major change in global climates

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recorded in marine and terrestrial sediments. A major cooling and ice volume event is inferred from terrestrail flora (Wolfe, 1978), as well as studies of $\delta^{18}O$ measurements on deep sea foraminifera (Miller et al., 1991). For example, the terrestrial record reveals a dramatic shift from a broad-leaved evergreen to a broad-leaved deciduous forest took place in the middle to high latitudes of Northern America (Wolfe, 1978). The marine record signals the growth and decay of ice sheets in Antarctica beginning in the Oligocene causing glacioeustatic changes from the Oligocene to Pleistocene (Miller et al., 1991).

The Miocene Epoch is also marked by major changes in global climate. General global warming in the late Oligocene to early Miocene was punctuated by at least 4 early Miocene glaciations (Mi1, Mi1a, Mi1b, and Mi2 of Miller et al., 1991). A major climatic transition began following the zenith of warmth in the late early to early middle Miocene (~17-15 Ma). A transient cooling/glaciation at ~16.5 Ma (= Mi2 of Miller et al., 1991) was followed by a warming and subsequent regrowth of the East Antarctic Ice Sheet from ~15-13 Ma (Miller et al., 1991; Flower and Kennett, 1994).

In this paper, we present pollen data collected from boreholes calibrated with Sr-isotope stratigraphy (excluding Island Beach). Stratigraphic nomenclature presented here is based on an informal numbering of Kirkwood sequences (Fig. 2). Previous concepts of the Kirkwood as a mappable lithostratigraphic unit with three distinct outcropping members or facies named Asbury Park, Grenloch Sand, Alloway Clay (Isphording, 1970), or as a subsurface unit consisting of water bearing sands separated by diatomaceous clay beds (Woolman, 1895) were modified into modern sequence concepts using diatom biostratigraphy (Andrews, 1988) and Sr-isotope stratigraphy (Sugarman et al., 1993). Three major (lower, middle, upper) Kirkwood sequences, with corresponding early Miocene, early/middle Miocene, and late middle Miocene ages were mapped by Andrews (1988) and Sugarman et al. (1993). Owens et al. (1995a; 1995b) redefined the Kirkwood Formation, and named three new formations for strata previously assigned to it, the Shiloh Marl, Wildwood, and Belleplain Formations (Fig. 2).

Recent Sr-isotope studies of the 150X-Atlantic City and 150X-Cape May coreholes (Miller and Sugarman, 1995) have extended the lower age range of the Kirkwood 1 sequence and termed it the Kirkwood 0 sequence (which is included in the Kirkwood 1a in this paper), subdivided the Kirkwood 2 sequence into separate sequences- the 2a and 2b, and identified another sequence above the Kirkwood 3 sequence, that may possibly correlate with the Cohansey Formation.

METHODS

Stratigraphic Sections

Stratigraphic sections (Figs. 3 and 4) were developed from published (and in press) studies of Miocene coreholes from in New Jersey Coastal Plain (Owens et al., 1988; Sugarman et al., 1993; Miller et al., 1994; in press; Miller and Sugarman, 1995; Owens et al., 1995a, 1995b). Stratigraphic sequences were identified as unconformity-bounded transgressive-regressive cycles of sedimentation which typically shoal upward. The typical "New Jersey cycle" consists of a basal glauconite sand, a middle silt, and an upper quartz sand, and is the result of progradation of deltaic deposits over marine shelf deposits. Unconformities were identified using physical stratigraphy, biostratigraphy, and Sr-isotope stratigraphy.

Palynology

This report uses previously published, unpublished, and new pollen data (Tables 2 and 3; Plates 1 and 2) for paleoclimatic interpretations of lower to middle Miocene sediments from the New Jersey Coastal Plain. Ager (in Owens et al., 1988) studied pollen from the ACGS#4 borehole. Ager (written communication, 1994) also made a preliminary analysis of pollen from Miocene sediments at the 150X-Island Beach borehole. Pollen from the Belleplain State Forest corehole was identified by Les Sirkin (written communication, 1991). New data presented in this study are chiefly from the 150X-Atlantic City corehole (Table 2), and the 150X-Cape May corehole (Table 3).

Paleoclimatic indicators were based on pollen genera outlined in Table 1. Three generalized climatic assemblages were identified, including: 1) warm temperate to subtropical; 2) temperate; and 3) cool to cold temperate. In addition, Table 1 lists genera indicative of swamp environments, and exotic genera including plants which are extinct or no longer grow in the region.

Picea, *Tsuga*, and to a lesser extent *Alnus* and *Abies*, are indicative of cool to cold temperate climates. *Alnus* and *Picea* have been documented as indicative of cool climates (Wolfe, 1978). A change to a *Picea* dominated forest from a broad leaf deciduous forest is primarily controlled by summer temperatures, as expressed by the 21° July isotherm (Wolfe, 1971). In North America, *Picea* is not native to areas of high summer heat (Wolfe, 1971). *Tsuga* typically prefers cool microhabitat found in gullies and higher altitudes. Other methods for paleoclimatic interpretation include the use of the *Pinus/Picea* ratio, with low ratios interpreted as intervals of climatic cooling (Goldstein, 1974), and the ratio of temperate-warm temperate taxa (*Carya*, *Quercus*, *Luiquidambar*, *Nyssa*, and *Ilex*) to subtropical-tropical taxa (*Momipites*, *Cyrilla*, Sapotaceae, and *Alangium*), with high ratios interpreted as cool intervals (Groot, 1992).

RESULTS

Kirkwood 1 sequence

The oldest of the Kirkwood sequences, the Kirkwood 1, is informally divided into the Kirkwood 1a and 1b sequence. The Kirkwood 1a sequence has Sr-isotope age estimates ranging from 23.8 to 20.4 Ma and corresponds to the Kirkwood Formation (as redefined by Owens et al., 1995a, 1995b). The Kirkwood 1b sequence ranges in age from 20.4 to 19.3 Ma, and is possibly as young as 18.6 Ma at the 150X-Cape May borehole; it is correlative with the Shiloh Marl Formation of Owens et al. (1995a, 1995b). A major disconformity separates the two sequences, although the length of the hiatus is below the limit of resolution of Sr-isotope stratigraphy (±0.4 m.y).

The Kirkwood 1a sequence contains a complex assemblage of shelf and deltaic facies. This sequence is an excellent example of a shoaling upward "New Jersey " sequence (e.g. see Sugarman et al., 1993, Fig. 1), with deeper water, finer grained shelf facies at the base, conformably grading upward into shallow water prodelta facies in the middle, and farther upward into coarser grained delta-front and nearshore marine facies. Spectacular shell beds at the 150X-AC borehole provided excellent samples for detailed Sr-isotope age estimates (Miller et al., 1994; Miller and Sugarman, 1995).

At Atlantic City (Fig. 3), the Kirkwood 1a sequence is approximately 200 ft thick. (Note: a summary of the Atlantic City and Island Beach boreholes may be found in Miller et al., 1994). The base of the sequence (~30 ft thick) is an assemblage of storm deposited shell beds and glauconite sand mixed in a clay-silt matrix deposited in a middle neritic shelf environment. Sr-isotope age estimates of 24-22 Ma for this section indicate excellent preservation of the lowermost Miocene. The sediment grades upward into seventy feet (~880-810 ft) of burrowed, laminated clay-silt, commonly containing fine shell hash or thin layers of shells, interpreted as prodelta facies. This clay-silt interval was deposited from 20.7-20.5 Ma based on Sr-isotope age estimates. A dramatic increase in sedimentation rates (230 ft/m.y.) measured in the prodelta facies (~880-810 ft) compared with the lower shelf facies (20 ft/m.y.) records a major influx of clastics in the lower Miocene at approximately 21 Ma..

At Atlantic City, the sequence is capped by ~70 feet of quartz sand, sporadically laminated, which was deposited in a shallow marine environment (based on the presence of sparse marine diatoms). No calcareous material was preserved in this interval for age dating; a 20.4 Ma Sr-isotope age estimate for the next sequence (Kirkwood 1b), at Atlantic City, provides a younger age limit for the Kirkwood 1a.

At the ACGS#4 corehole, both the Kirkwood 1a and 1b sequences shoal upward. The Kirkwood 1a is 100 feet thick, with Sr-isotope age estimates of 21.4-20.9 Ma. This lithofacies grades upward from a thin (~5 ft) burrowed clayey glauconitic fine sand, to a somewhat thicker (~20 ft) laminated micaceous, clayey silt, to a thick (50 ft) laminated clay silt with interbeds of massive silty fine sand, and scattered shell fragments (Owens et al., 1988). The sequence is capped by 25 feet (compared with 70 feet at Atlantic City) of coarse sand grading upward into fine gravel. The Kirkwood facies are typical middle neritic shelf facies at the base, grading upward into prodelta, and finally to inner neritic shelf to nearshore facies.

The contact of the Kirkwood 1a and 1b sequences is marked by a 3 ft thick reworked bed consisting of medium to coarse sand and gravel, broken mollusk shells, pyrite, and fine organic matter. The lower clay-silt facies of the Kirkwood 1b sequence is ~45 feet at the ACGS#4 borehole. The sediment consists of laminated to thinly intercalated silt and very fine sand containing mica, finely dispersed carbonaceous material, and occasional broken shell material, consistent with deposition of prodelta facies (Owens et al., 1988).

The upper sand facies of the Kirkwood 1b sequence at the ACCS#4 corehole is 90 ft thick, and is typically an olive-gray medium to coarse quartz sand with thick shell beds deposited in an inner neritic to nearshore shelf environment (Owens et al., 1988). Sr-isotope age estimates are 20.4-19.7 Ma, and sedimentation rates were relatively rapid in the quartz sand facies.

At Island Beach, the Kirkwood 1a sequence contains only a thin weathered shell bed at its base (Sr-isotope age estimates of 21.8-21.7 Ma) for constraints on the lower age of this sequence. Additionally, key diatom markers were absent preventing any correlations with ECDZ 1 (Miller et al., 1994). Therefore, correlations of this interval with the Kikwood 1 sequence at Atlantic City and the ACGS#4 are tentative.

At Island Beach, the Kirkwood 1a is more than 200 ft thick, and contains a greater percentage of coarse clastics. Dinoflagelate cysts and diatom fragments suggest that the environment of deposition was brackish to shallow marine.

Pollen Assemblages and Paleoclimate

Overall, pollen preserved in the Kirkwood 1a and 1b sequences at the Island Beach, Atlantic City, and the ACGS#4 boreholes is dominated by temperate to warm temperate forest vegetation (Fig. 3). *Quercus-Carya-Pinus* is typically the dominant assemblage. Other common to occasional genera include *Tsuga, Betula, Carya, Ilex, Podocarpus, and Engelhardia.* At the ACGS#4 corehole, a *Fagus-Quercus* assemblage, with lesser amounts of *Quercus*, *Carya*, *Pinus*, and *Ulmus*. was reported as the dominant assemblage in the Kirkwood 1 sequence (Owens et al., 1988). At Island Beach, relatively small amounts of *Pinus* were observed (T. Ager, U.S. Geological Survey, written communication, 1994).

Although the majority of samples contained warm temperate to temperate pollen assemblages, some indications of cooler paleoclimates were found at the base of the Kirkwood 1a sequence at Island Beach (498 ft and

475 ft) and near the base at Atlantic City (850 ft). A well preserved sample from 850 ft at the Atlantic City borehole (Sr-isotope age estimate of 20.6 Ma) contained abundant *Quercus*, common *Ilex*, *Poplar*, *Taxus*, and *Tsuga*, and occasional *Picea*, *Carya*, *Nyssa*, *Engelhardia*, *Tilia*, *Alnus*, *Castanea*, *Pterocarya*, and *Betula* (Table 2). The mixture of spruce, hemlock, alder, and birch suggests a cool temperate climate with evidence of boreal forest assemblages existing near the source area. Groot (1992) also reports a minor cool interval in the lower Miocene near the base of the Calvert Formation. At Island Beach, samples from the base of the Kirkwood 1 sequence contained a higher diversity and greater abundance of conifer pollen (e.g. Pinaceae and Taxodiacea), along with *Picea* and *Alnus*, suggesting possible cooler (temperate instead of warm temperate) climatic conditions.

Kirkwood 2 Sequence

A major unconformity separates the Kirkwood 1 and Kirkwood 2 sequences; at Atlantic City the hiatus is 2.0 m.y. (Figs. 3 and 4). The Kirkwood 2 spans the lower/middle Miocene boundary, and has been subdivided into the 2a and 2b sequences (Miller et al., 1994; Miller and Sugarman, 1995); a hiatus of ~0.6 m.y. separates these sequences at the Atlantic City borehole (Fig. 4). The sequence is correlative with ECDZ 2 (Andrews, 1988; Sugarman et al., 1993). The Kirkwood 2 sequences are equivalent to the Wildwood Formation of Owens et al., 1995b.

The 2a and 2b sequences are predominantly clay-silt, and are difficult to differentiate based on lithology or facies alone. As a result, chronostratigraphic methods, including diatom biostratigraphy and Sr-isotope stratigraphy are necessary for stratigraphic subdivision.

The Atlantic City corehole provides an excellent reference section for the Kirkwood 2a sequence, where it is ~150 feet thick (Fig. 4). Here, the sequence is dominatly a micaceous, laminated clay-silt and fine sand, with thin shell intervals. Certain beds are mostly fine sand; their environment of deposition is interpreted as marine deltaic (prodelta). Sandy-silty and silty sandy shell beds, to sandy shell beds deposited in inner neritic shelf environments are also present. For instance, a shelly sand occurs at the top of the Kirkwood 2a sequence in the Atlantic City borehole. Sr-isotope ages for the Kirkwood 2b sequence range from 18.1-16.9 Ma in the Atlantic City borehole at ~520-510 ft.

The Kirkwood 2b sequence is 42 ft thick at Atlantic City; Sr-isotope age estimates are 16.3-15.8 Ma. At Atlantic City, the 2b sequence is typically a burrowed clay-silt with some shelly zones; the environment of deposition is interpreted as inner neritic shelf.

At Belleplain State Forest, the corehole penetrated the upper part of Kirkwood 2a, along with a complete section of Kirkwood 2b (Fig. 4). The Kirkwood 2b sequence is 46 ft thick at Belleplain (almost identical to the 42 ft thickness at Atlantic City), with Sr-isotope age estimates of 16.1-15.5 Ma (Sugarman et al., 1993). Depositonal facies in the 2b sequence grade from inner neritic in the lower half to prodelta in the upper half. A 1 m.y. hiatus separates the 2b from the 2a sequence; the surface is marked by a lag deposit.

The Kirkwood 2a and 2b sequences were also present at the 150X-Cape May borehole (Fig. 4). Sparse Sr-isotope age estimates are 17.8 - 16.9 Ma from the 2a sequence, and 16.3-16.2 Ma from the 2b sequence. The Kirkwood 2a sequence at Cape May is ~95 feet thick., and is a good example of a shoaling upward "New Jersey sequence". A shell bed marks its base. Above this, laminated clays with scattered shells grade upward into interbedded fine to medium sands and laminated clays. The sequence is capped with fine to medium sands with scattered interbedded sandy clays. Again, the coarser grained sand facies at the top of the 2a sequence is relatively thin (~10 ft), compared with the thick sand facies at the top of the Kirkwood 1 sequence. The 2b sequence is about 40 feet at Cape May. Recovery of this interval was poor; the base of this sequence consisted of shell hash in a clay-sand matrix.

Pollen Assemblages and Paleoclimate

The Kirkwood 2 sequence(s) contain a more varied record of climatic change than the Kirkwood 1 sequence. At the 150X-AC borehole, palynological results indicate that the transgressive deposits at the base of the Kirkwood 2a sequence at 662 ft and 656 ft record warm to subtropical paleoclimates where *Quercus* and *Carya* are the dominant taxa, with lesser *Engelhardia* and *Planera*. A transition from warm temperate to temperate paleoclimates is recorded slightly higher in the corehole (649 ft, 632 ft). The dominant taxa are similar to those from 662 ft and 656 ft, with the addition of *Pinus* at 649 ft. Other than the rare presence of *Cyrilla*, no evidence of warmer paleoenvironments is present at 649 ft or 632 ft.

A major transition to cooler climates is observed in the regressive sediments from the upper part of the Kirkwood 2a sequence (Fig. 4). In this interval, the dominant assemblage changes from *Quercus* and *Carya*, to *Quercus, Picea, and Carya,* a cool to cold temperate assemblage. In addition, *Tsuga* and *Alnus* , also indicative of cool climates, are present, but only in trace amounts. The assemblage from 525 ft also includes small amounts of *Pinus*, *Betula*, *Fagus*, and *Tilia*. Overall, the Kirkwood 2a sequence from the 150X-AC borehole can be characterized as an upward cooling sequence (Fig. 4).

Pollen data from the Belleplain borehole come from the upper part of the Kirkwood 2a sequence (330 ft and 311 ft; Sr age estimate of 17.0 Ma). The sample at 311 ft contains *Pinus* and *Picea,* in addition to the exotics *Clethra, Podocarpus, Cyrilla, Engelhardia/Momipites, Symplocus* and *Gordonia.* This sample contains both warm temperate to subtropical trees and exotics, and warm to cool temperate trees with spruce (L. Sirkin, Adelphi University, written communication, 1991). The sample from 330 ft contained a less diverse assemblage dominated by *Quercus, Carya*, and *Pinus*, with lesser

Engelhardia and Planera. This limited assemblage is typical of warm temperate to temperate paleoclimates.

At the 150X-Cape May borehole, a *Quercus, Picea, and Carya* dominated assemblage, indicative of cool to cold temperate environments, was identified at 653 ft and 637 ft (Table 3). The assemblage at 653 ft also contained sparse *Alnus* and *Tsuga,* whereas at 637 ft *Betula, Fagus, Pterocarya,* and *Acer* are sparsely present. At 663 ft, a sample with poor pollen recovery suggested a possible temperate paleoclimate. The Kirkwood 2a sequence at Cape May also contains cool palynological assemblages in the upper, regressive part of the sequence.

Limited palynological data from the Kirkwood 2b sequence at Atlantic City (509 ft) and Belleplain (270 ft) are dominated by temperate (and to a lesser extent cool temperate) assemblages. The limited stratigraphic thickness of the Kirkwood 2b (30-50 ft), coupled with lack of recovery at Cape May, and minimal potential for palynological recovery in certain sandy horizons, suggests that limited paleoclimatological information can be recovered from this sequence.

Kirkwood 3 Sequence

Representative Sr-isotope and paleoclimatic sections of the Kirkwood 3 sequence are obtained from the Belleplain State Forest and Atlantic City coreholes (Fig. 4). At Belleplain, the Kirkwood 3 sequence is ~150 ft thick. Sr-isotope ages for the lower 30 ft of the sequence gave estimates (in inverse order) of 12.3-13.2 Ma (Sugarman et al., 1993). This interval also contained diatoms assigned to uppermost ECDZ#5/lowermost ECDZ#6 (G. Andrews, written communication, 1992). The Kirkwood 3 sequence is correlative with the newly named Belleplain Formation of Owens et al. (1995b).

At Belleplain, depositional facies of the Kirkwood 3 sequence differ from the typical "New Jersey sequence" in that they shallow from the base to the top, but do not coarsen. This reflects the transition from inner neritic shelf to prodelta to tidal flat facies; the upper tidal flat facies contains abundant finely laminated clay-silt in contrast to the typical delta front or barrier beach facies which commonly cap the typical shoaling-upward sequence.

At Atlantic City, sediments recovered from this sequence were bioturbated laminated clay-silts with small shell fragments and shell hash. This facies is consistent with prodelta and shallow shelf deposition (Owens et al., 1988; Sugarman et al., 1993). Sr-isotope age estimates range from 13.8 to 13.1 Ma (Miller et al., 1994). Sedimentation rates are relatively high; between 463 ft (13.7 Ma) and 402 ft (13.3 Ma), sedimentation rates are ~150 ft/m.y.

Pollen Assemblages and Paleoclimate

The base of the Kirkwood 3 at the 150X-AC borehole (463 ft) contains a dominant *Quercus, Fagus, Ulmus* assemblage, along with minor percentages of taxa indicative of warm to subtropical paleoenvironments (Table 2). Sixteen feet higher in the borehole at 447 ft, common *Picea, Alnus,* with occasional *Tsuga* and *Abies,* characteristic of cool temperate conditions, signal a major change in paleoclimatic assemblages. At 432 ft, the assemblage is dominated by *Quercus, Picea,* and *Tsuga,* cool to cold temperate assemblage. The Kirkwood 3 sequence at the 150X-AC borehole also appears to cool upward into the regressive section of the sequence, similar to the Kirkwood 2a sequence.

At the base of the Kirkwood 3 sequence at the Belleplain State Forest borehole, a mixture of cool and warm temperate pollen assemblages were present at 236 ft (Sr-isotope age of 13.0 Ma). The sample contained a *Quercus, Carya,* and *Pinus* dominated suite, along with abundant *Picea,* and rare exotics indicative of warm temperate to subtropical conditions including *Podocarpus, Planera, Engelhardia/Momipites, Cyrilla,* and *Symplocus.* Additional samples from the Kirkwood 3 sequence at the Belleplain corehole at 216 ft and 115 ft contained a poorly preserved warm temperate assemblage. Overall, the Kirkwood 3 sequence at Belleplain has some cool climatic indicators at its base, with the limited data indicating a warming trend upward.

DISCUSSIONS AND CONCLUSIONS

Overall, the pollen assemblages from the Kirkwood 1 sequence (~22-20 Ma) represent temperate to warm temperate predominantly broadleaf, deciduous forest vegetation. The dominance of *Quercus, Carya,* and *Pinus* pollen, along with the minor presence of taxa which grow in subtropical to tropical regions, suggest that a warm temperate climate prevailed during the lower Miocene. Some minor intervals of climatic variation may have marked this period of relative climatic stability. For example, the pollen sample from the 150X-Atlantic City corehole at 850 ft contained a cooler assemblage, including *Picea, Tsuga,* and *Alnus* , indicating a cooler climatic interval at 20.6 Ma.

The long hiatus (e.g. 20.2-18.1 Ma at the 150X-AC corehole) between the Kirkwood 1 and 2 sequences precludes any possible palynologic analysis and paleoclimatic interpretations for this lower Miocene interval. However, a change in palynologic assemblages in the Kirkwood 2 sequence beginning at ~17.8 Ma, records a major climatic transition in the late early Miocene. *Picea* becomes common between 575 and 525 ft, whereas taxa indicative of warm temperate to subtropical conditions are rare above 650 ft in the 150X-AC corehole. A similar cooling trend is evident in the 150X-Cape May corehole (Fig. 4; Table 2).

The paleoclimatologic data from the New Jersey Coastal Plain record a climatic transition at ~17.8-17 Ma; this is at least 1 m.y. prior to the timing of this event based on integrated data sets (Flower and Kennett, 1994) including the deep sea $\delta^{18}O$ record (Miller et al., 1991). Groot (1992) suggested that the cooler taxa preserved in coastal plain deposits may not be controlled by climate, but by relative sea level. For example, during transgressions and times of higher sea level, pollen may be derived directly from the regions of higher elevation than the Coastal Plain, such as the Piedmont or Appalachians, allowing higher percentages of cooler taxa to be preserved.. This study does not confirm this hypothesis as the warmer assemblages have been found at the base, or transgressive section of the Kirkwood 2a sequence, whereas the cooler assemblages occur in the regressive, or shallower water facies.

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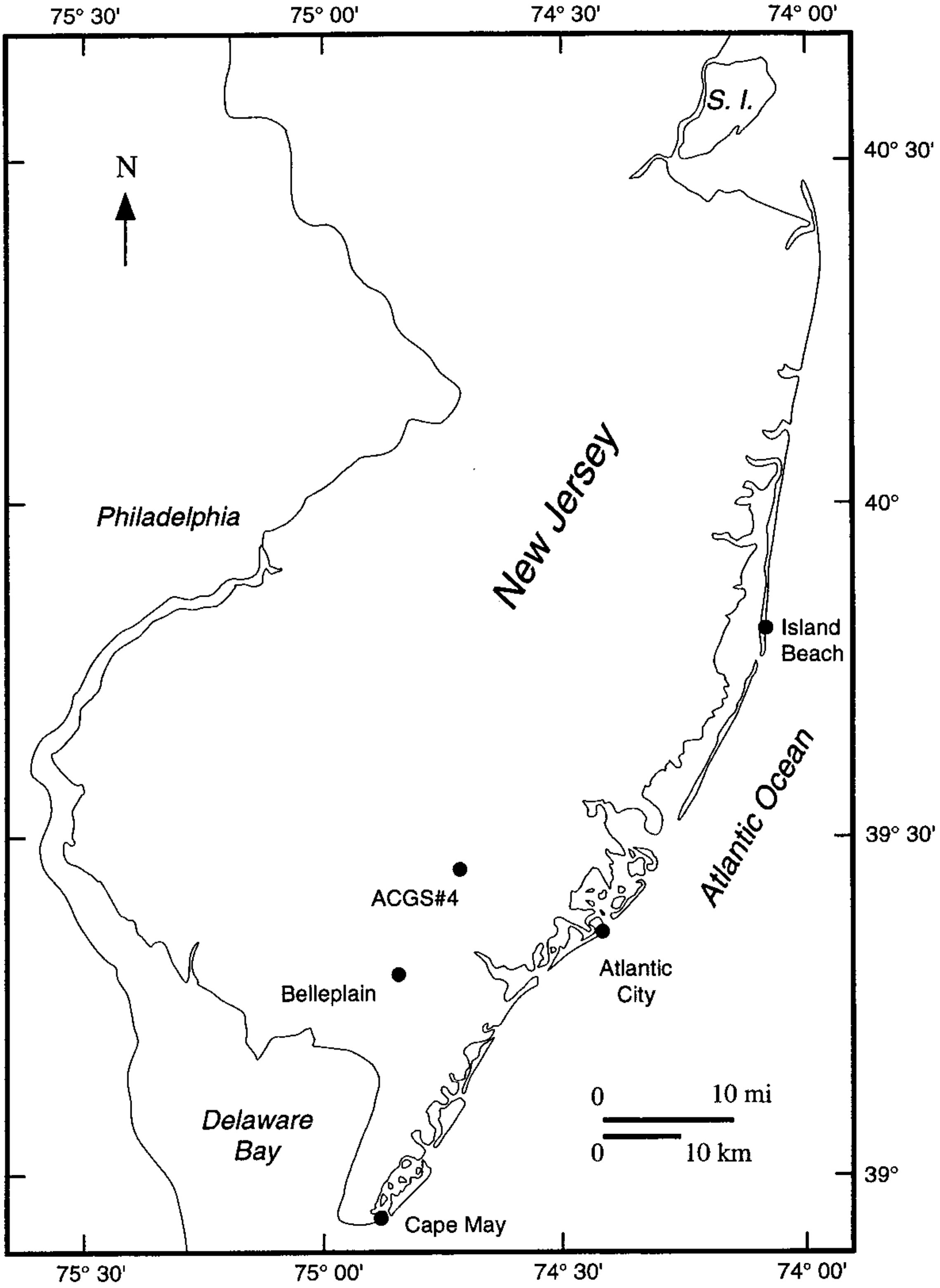


Fig. 1. Location of boreholes used in study.

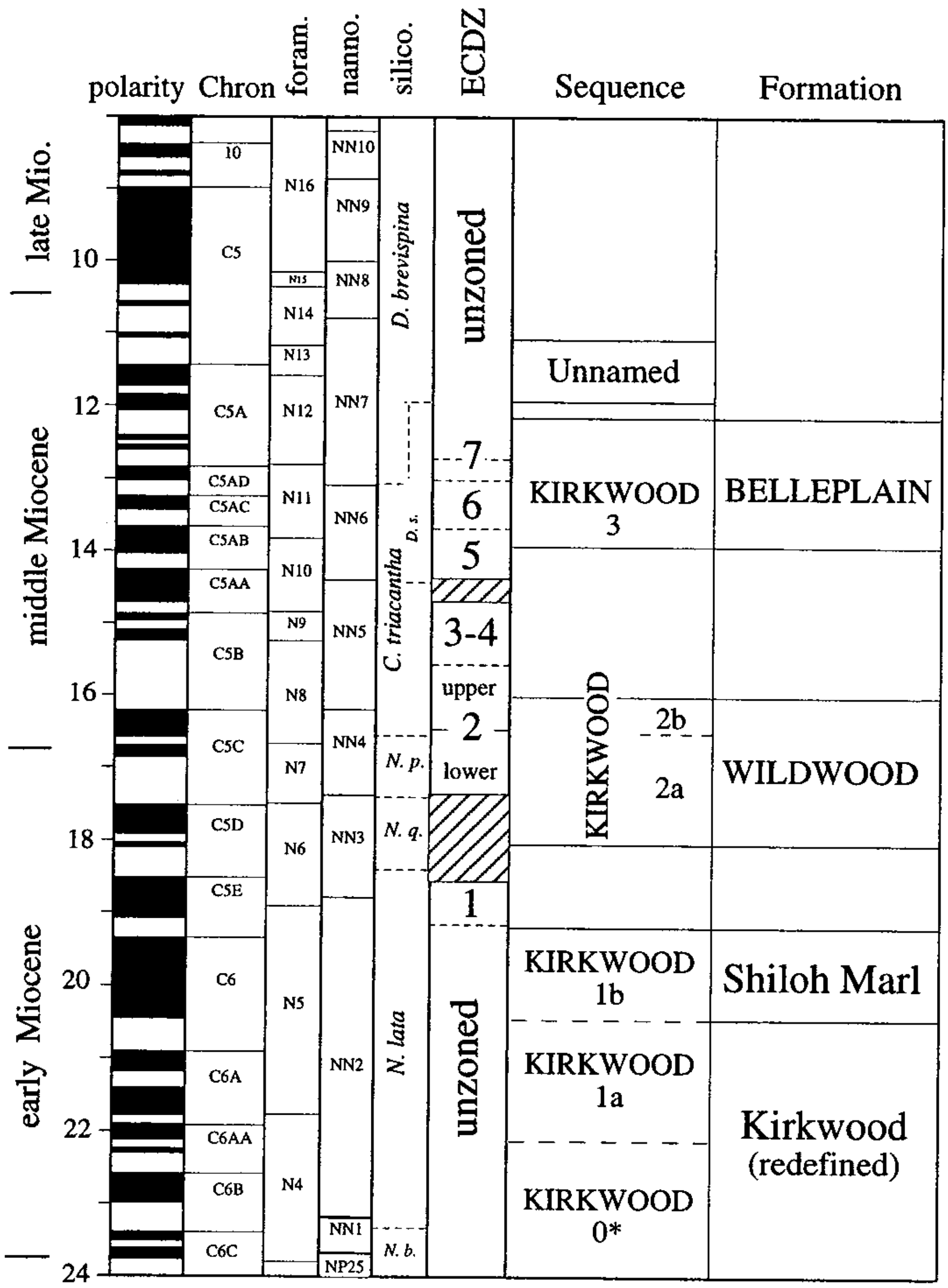


Fig. 2. Correlation of lower to middle Miocene sequences and geologic formations in New Jersey, with the Geopolarity Magnetic Timescale and planktonic foraminiferal zones of Berggren and others (1985), silicoflagellate zonation of Bukry (1981) using his silicoflagellate-nannofossil correlations, and the East Coast Diatom Zones of Andrews (1988). *N. b.* = *N. biapiculata; N. q.* = *N. quadrata; N. p.* = *N. punticula; D. s.* = *D. stauracanthus*. *Note that the Kirkwood 0 sequence of Miller and Sugarman (1995) is included in the Kirkwood 1a sequence in this report.

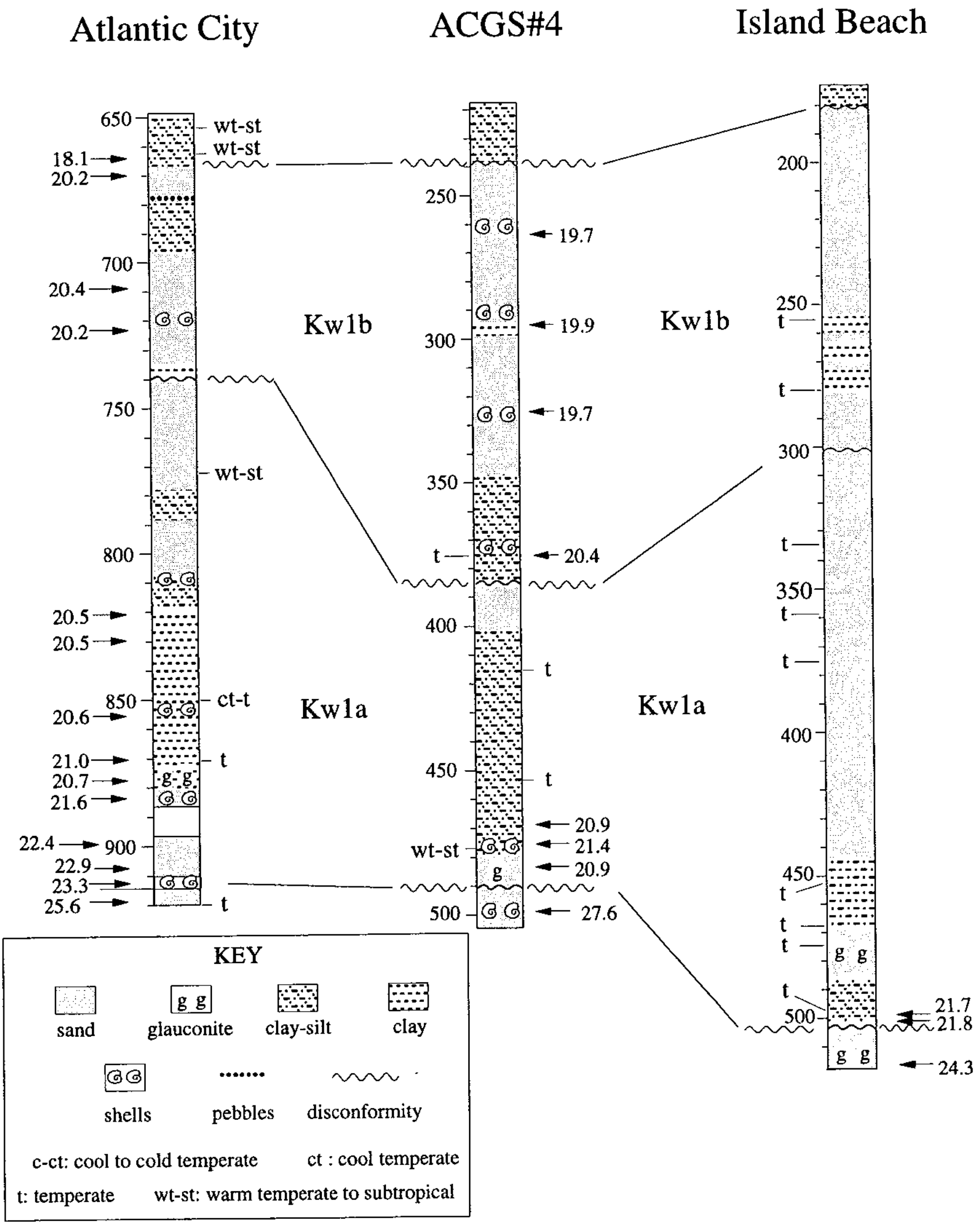


Figure 3. Correlation of the Kirkwood 1 sequence at the Atlantic City, ACGS#4, and Island Beach coreholes. Also shown are Sr-isotope age estimates (in Ma), and intervals of palynological sampling and paleoclimatic interpretation. Depths in feet below land surface.

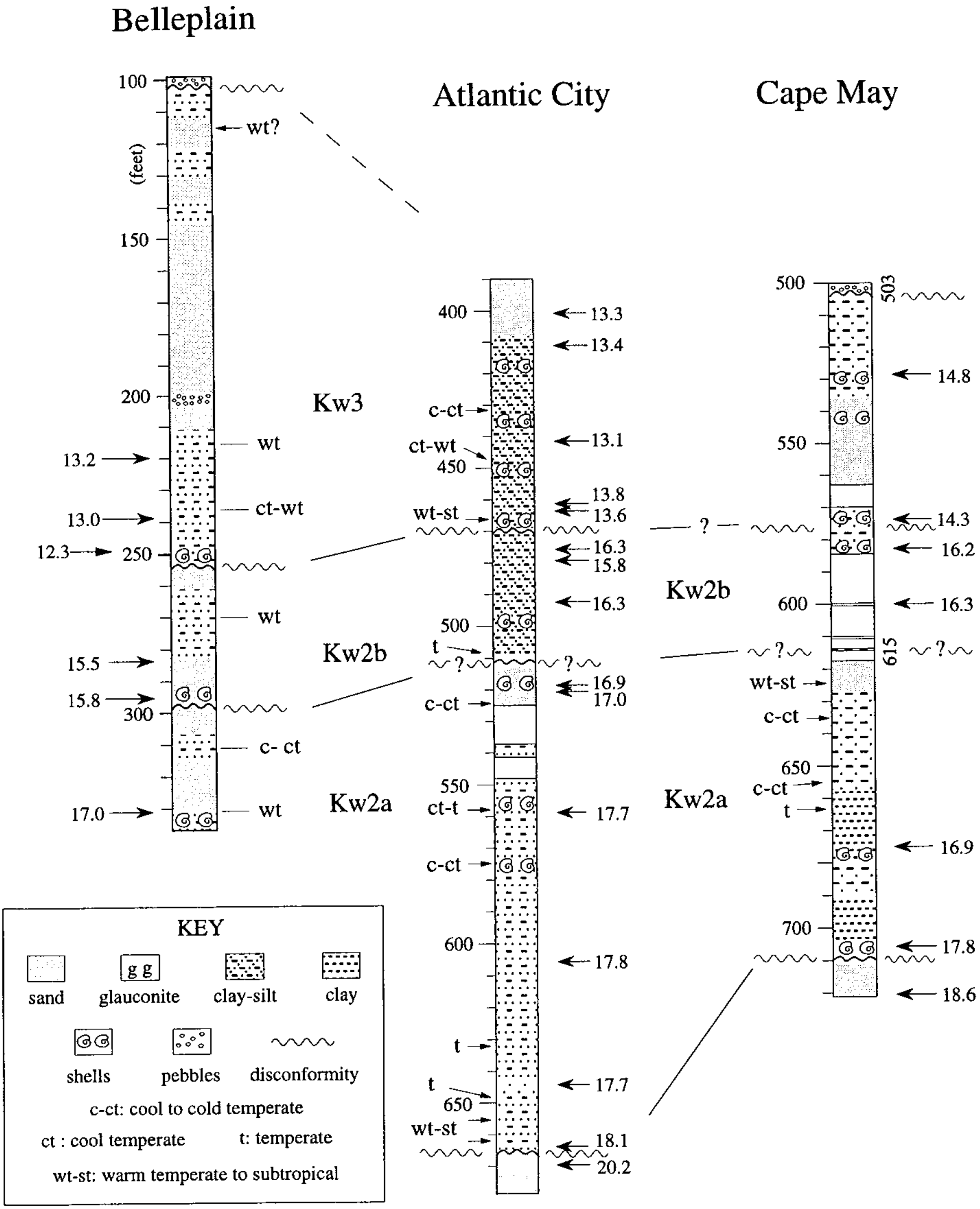


Figure 4. Correlation of the Kirkwood 2 and 3 sequences from the Belleplain, Atlantic City, and Cape May coreholes. Also shown are Sr-isotope age estimates (in Ma), and intervals of palynological sampling and paleoclimatic interpretation. Depths in feet below land surface.

Warm Temperate to Subtropical Genera

Engelhardia
Alangium
Manilkara
Cyrilla
Planera
Gordonia
Symplocos
Podocarpus
Taxodium
Glyptostrobus
Jussiaea
Cyathea
Nyssa
Magnolia

Temperate Genera

Carya
Quercus
Luiquidamber
Nyssa
Ilex
Fagus
Tilia
Castanea
Ulmus
Pterocarya

Cool to Cold Temperate Genera

Picea
Abies
Alnus
Tsuga

Swamp-Associated Genera

Engelhardia
Alnus
Ilex
Liquidamber
Nyssa
Planera
Symplocos
Taxodium
Glyptostrobus
Cyrilla

Exotic Genera

Glyptostrobus
Engelhardia
Pterocarya
Alangium
Symplocos
Podocarpus

Table 1. Climatic and paleoenvironmental indicator Genera.

MARINE MICROPLANKTON	X				X		X		X		X	X	X	
PALEOCLIMATE	TEMPERATE	TEMPERATE	COOL TO TEMPERATE	WARM TO SUBTROPICAL	WARM TO SUBTROPICAL	WARM TO SUBTROPICAL	TEMPERATE	TEMPERATE	COOL TO TEMPERATE	COOL TO COLD TEMPERATE	COOL TO COLD TEMPERATE	TEMPERATE	WARM TO SUBTROPICAL	COOL TO WARM TEMPERATE
DOMINANTS	PINE-HICKORY	PINE- OAK	OAK-HICKORY-HEMLOCK	OAK-PINE	HICKORY	OAK-HICKORY	OAK-HICKORY-PINE	OAK-HICKORY	OAK-SPRUCE HICKORY	OAK-SPRUCE HICKORY	OAK-SPRUCE-HICKORY	OAK-HICKORY	OAK-BEECH-ELM	OAK-SPRUCE-PINE
SAMPLE DEPTH	920-970ft.	870ft.	850ft.	773ft.	662ft.	656ft.	649ft.	632ft.	575ft.	554ft.	525ft.	509ft.	467.2ft.	447ft.
Palynological recovery		fair	excellent	poor	poor	fair	poor	fair	good	excellent	good	good	excellent	excellent
SEQUENCE	?		1a	1a	2a	2a	2a	2a	2a	2a	2a	2b	3	3
Sr-isotopic Age	25.8Ma	21.0Ma	20.8Ma		17.9Ma	17.7Ma		17.8Ma	17.7Ma	17.7Ma	17.0Ma			13.5Ma
COOL/COLD GENERA														
PICEA	R		O	R			R	O	C	C	C	R	R	C
ABIES												O	R	O
TSUGA			C	R						R	R		R	O
ALNUS			O						R	R		O	R	C
TEMPERATE GENERA														
PINUS	C	A		O			C	O		R	O		R	C
BETULA			O				R	R	R	O	O		R	R
CARYA	A		C	R	C	O	A	C	C	C	C	A		C
QUERCUS	O	C	A	O		C	A	A	A	A	A	A	A	A
LIQUIDAMBER					R					R			R	C
FAGUS				R			R		R	R	O	R	C	R
TILIA		O	O			R					O	R		R
ULMUS							R		R	R		R	O	C
PTEROCARYA								R			R			
ILEX			C						C			R	R	
CASTANEA			O				R					R		
JUGLANDS			R								R			
ACER											R		R	R
WARM TEMPERATE TO SUBTROPICAL														
ENGELHARDIA	R		O			O					R	C	R	R
ALANGIUM														
MANILKARA													R	
CYRILLA				R									R	
PLANERA													R	
GORDONIA			R			O	R							
SYMPLOCOS													R	R
PODOCARPUS		O	R	R								X	R	R
TAXODIUM		R			R									
PLANERA													O	
GLYPTOSTROBUS														
JUSSIAEA				R										
CYATHEA						R						X		
NYSSA			R			R					R			R
CYCADACEAE														
OSTRYA			R	R	R									
MAGNOLIA			R											

(R = RARE = LESS THAN 1%) (O = OCCASIONAL = 1-5%) (C = COMMON = 6 - 10 %) (A = ABUNDANT = GREATER THAN 10%)

Table 2. Pollen assemblages and paleoclimates of the 150X-Atlantic City corehole.

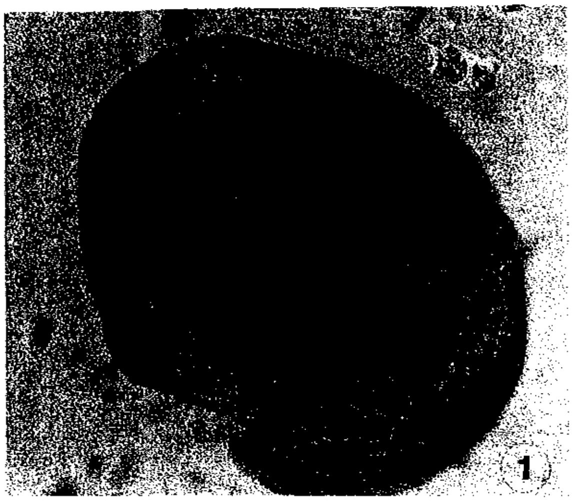
MARINE MICROPLANKTON	X		X		
PALEOCLIMATE	?	TEMPERATE	COOL-COLD TEMPERATE	COOL-COLD TEMPERATE	WARM TO SUBTROPICAL
DOMINANTS			SPRUCE PINE-OAK	SPRUCE PINE-OAK	
SAMPLE DEPTH	673-673.8ft.	663.2ft.	651.4ft.	636.6 -636.8ft.	620.4-620.6.8ft.
Palyn. Recovery	Very Poor	Poor	good	good	poor
SEQUENCE	2a	2a	2a	2a	2a
Sr-Isotopic Age	Ca. 16.9 Ma		Ca. 16.8Ma	Ca. 16.6Ma	Ca. 16.5Ma
COOL/COLD GENERA					
PICEA	X	X	C	A	
ABIES		X			
TSUGA			O	R	O
ALNUS			O		
TEMPERATE GENERA					
PINUS		X	A	C	O
BETULA				O	R
CARYA	X		C	C	O
QUERCUS			A	C	R
LIQUIDAMBER					R
FAGUS		X		O	
TILIA					
ULMUS					
PTEROCARYA				O	
ILEX					
CASTANEA					
JUGLANDS		X			
ACER				O	R
WARM TEMPERATE TO SUBTROPICAL					
ENGELHARDIA					
ALANGIUM					
MANILKARA					
CYRILLA					R
PLANERA					
GORDONIA					
SYMPLOCOS					
PODOCARPUS					
TAXODIUM					R
PLANERA					
GLYPTOSTROBUS					
JUSSIAEA					
CYATHEA					R
NYSSA					
CYCADACEAE					
OSTRYA					
MAGNOLIA					

(R = RARE = LESS THAN 1%) **(O = OCCASIONAL = 1-5%)**
(C = COMMON = 6 - 10 %) **(A = ABUNDANT = GREATER THAN 10%)** **(X= PRESENT-USED IN VERY POOR RECOVERY)**

Table 3. Pollen assemblages and paleoclimates of the 150X-Cape May corehole.

PLATE 1. Common lower to middle Miocene pollen taxa, 150X-Atlantic City and Cape May coreholes.

FIGURE	GENUS	CORE SAMPLE	MAXIMUM DIAMETER
1.	*Picea* (Spruce)	CM 150x 636.6'-636.8'	140.4 µm
2.	*Pinus* (Pine)	AC 150x 431.7'-432'	71 µm
3.	*Tsuga* (Hemlock)	CM 150x 636.6'-636.8'	91 µm
4.	*Quercus* type 1	AC 150x 467.2'-467.4'	29 µm
5.	*Quercus* type 2	AC 150x 467.2'-467.4'	35 µm
6.	*Acer* (Maple)	AC 150x 467.2'-467.4'	34 µm
7.	*Fagus* (Beech)	AC 150x 431.7'-432'	35 µm
8.	*Tilia* (Linden)	CM 150x 651.4'	37 µm
9.	*Carya* (Hickory)	CM 150x 651.4'	43 µm
10.	*Betula* (Birch)	CM 150x 636.6'-636.8'	31 µm
11.	*Betula* (Birch)	CM 150x 651.4'	22 µm
12.	*Alnus* (Alder)	AC 150x 431.7'-432'	23 µm
13.	*Ulmus* (Elm)	AC 150x 431.7'-432'	29 µm
14.	*Liquidamber* (Sweet Gum)	AC150x 431.7'-432'	31 µm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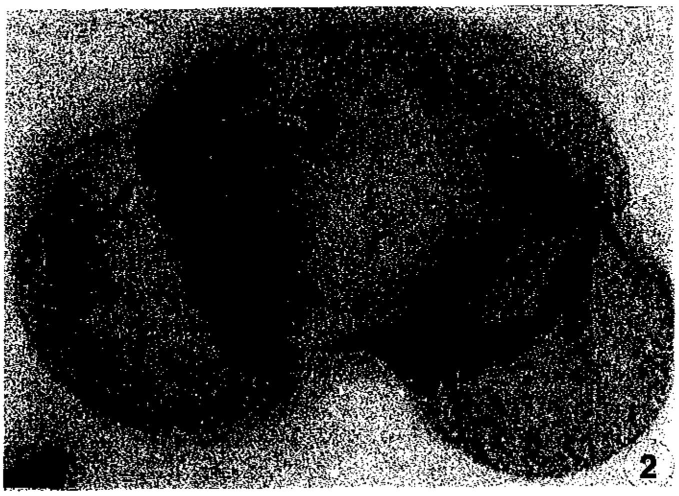
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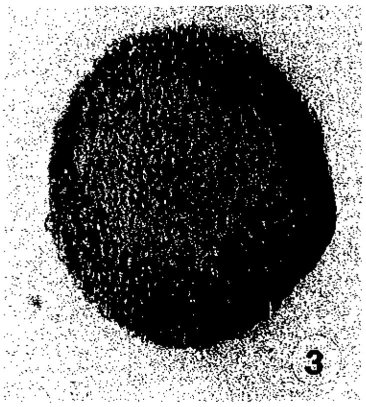
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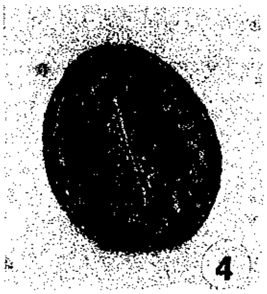
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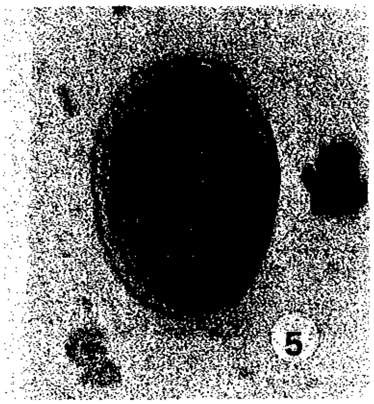
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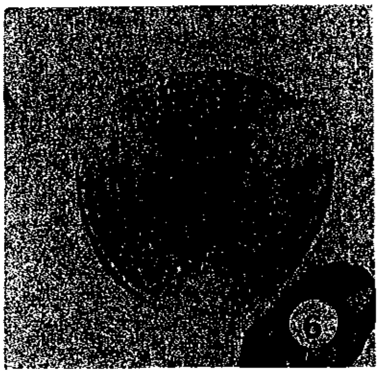
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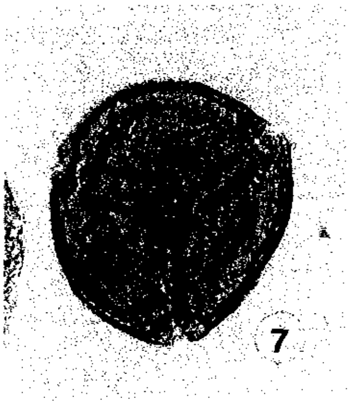
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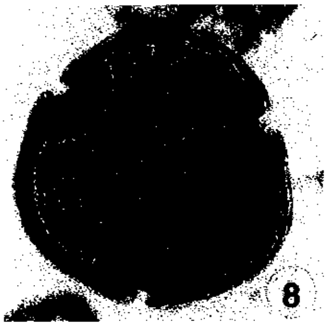
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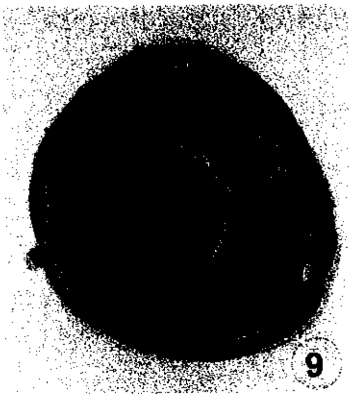
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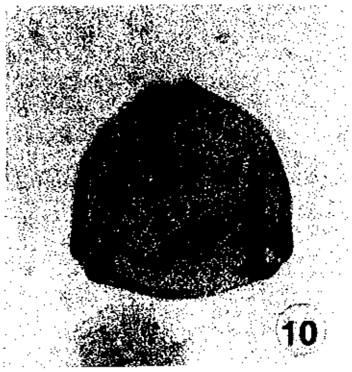
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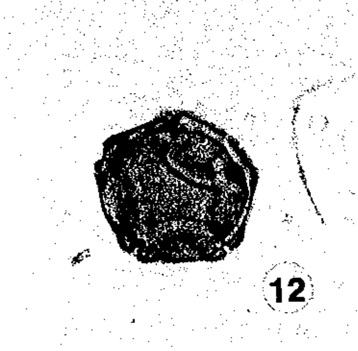
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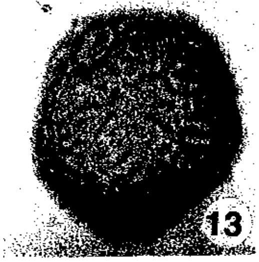
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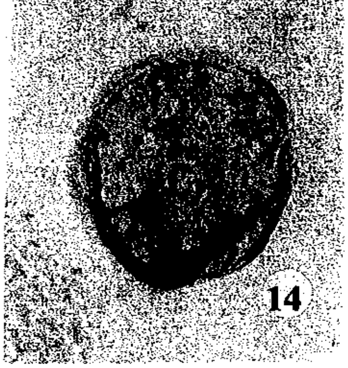
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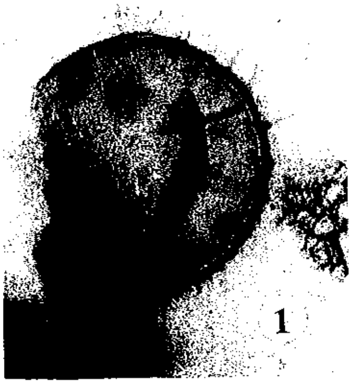
PLATE 2. Rare and exotic lower to middle Miocene pollen taxa, 150X-Atlantic City and Cape May boreholes.

FIGURE	GENUS	CORE SAMPLE	MAXIMUM DIAMETER
1.	*Nymphea* (Water Lily)	AC 150x 467.2'-467.4 '	38 µm
2.	*Castanea* (Chestnut)	AC 150x 467.2'-467.4 '	12 µm
3.	Compositae-Tubuliflorae	AC 150x 431.7'-432'	28 µm
4.	Gramineae (Grass)	AC 150x 467.2'-467.4 '	34 µm
5.	*Chenopodium* (Goosefoot)	AC 150x 431.7'-432'	21 µm
6.	*Ephedra*	CM 150x 651.4'	53 µm
7.	*Podocarpus* type 1	AC 150x 447'-448 '	107 µm
8.	*Podocarpus* type 2	AC 150x 447'-448 '	70 µm
9.	*Magnolia*	AC 150x 431.7'-432'	42 µm
10.	*Nyssa* type 1 (Gum)	AC 150x 447'-448 '	34 µm
11.	*Nyssa* type 2 (Gum)	AC 150x 431.7'-432'	34 µm
12.	*Gordonia*	AC 150x 467.2'-467.4 '	30 µm
13.	*Engelhardia*	AC 150x 467.2'-467.4 '	24µm
14.	*Symplocos*	AC 150x 467.2'-467.4 '	23 µm
15.	*Pterocarya*	CM 150x 636.6'-636.8'	26 µm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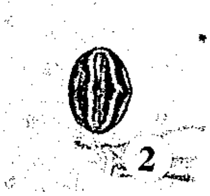
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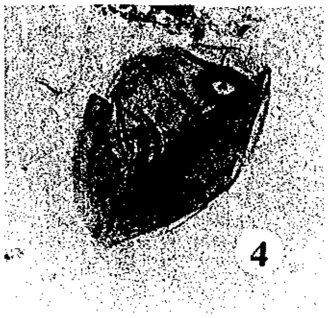
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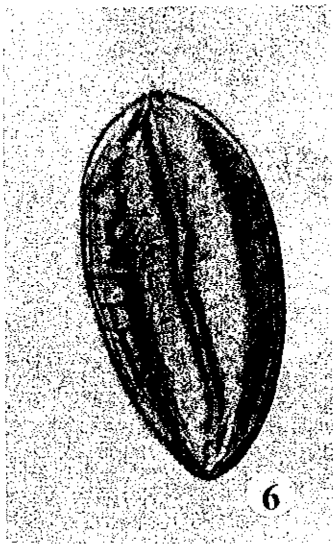
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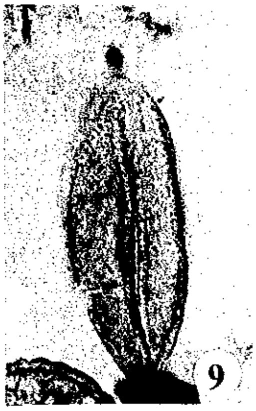
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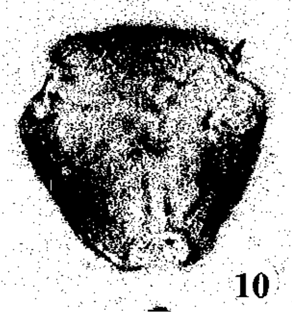
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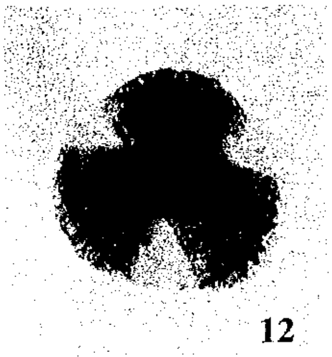
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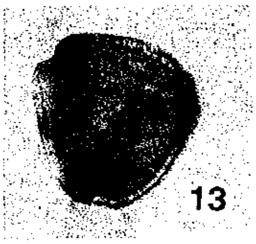
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Miocene Diatom Biostratigraphy of New Jersey

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ABSTRACT

Three separate deposits of Miocene diatomaceous strata have been identified in New Jersey. The oldest of these was deposited in rocks of Early Miocene (Burdigalian) age, dated between 18 and 18.5 Ma. The second was deposited in rocks of late Early Miocene to early Middle Miocene (late Burdigalian to early Langhian) age, dated between about 15.5 and 17.0 Ma. The youngest Miocene diatomaceous deposit was laid down in rocks of Middle Miocene (Serravallian) age, dated between About 13.5 and 13.9 Ma. These New Jersey diatomaceous strata have been correlated with deposits of Miocene age in the more nearly continuous stratigraphic sections in Maryland and Virginia as well as with the fossil zones of other microorganisms.

INTRODUCTION

The sedimentary rocks of the Atlantic Coastal Plain of New Jersey were delineated as early as the mid-eighteenth century, and a summary of the early stratigraphic investigations and nomenclature is given by Spangler and Peterson (1950, p. 7-15). The earliest report on Miocene diatoms from New Jersey was made by Kain and Schultze (1889) on the diatoms from an artesian well in Atlantic City. Woolman (1891) described more extensively the stratigraphic section in the artesian wells at Atlantic City. Woolman (1892) further described the Miocene diatomaceous deposits found in the Atlantic City wells and suggested their correlation with certain Miocene deposits in Maryland and Virginia. The most comprehensive early report on the stratigraphic occurrence of fossil diatoms in New Jersey was made by Woolman (1895, p. 160-172) on the diatomaceous strata found in a well near Wildwood, Cape May County. Woolman recognized four distinctive diatomaceous deposits in this well. The uppermost, which he termed "Diatom bed no. 1" occurred from depths of 29 to 46 feet (9 to 14 m) and contained a modern marine diatom assemblage, probably of either Pleistocene or Holocene age. Woolman's "Diatom bed no. 2" contained a mixture of marine and nonmarine diatoms of probable Pleistocene age. Neither Woolman's "bed 1" nor his "bed 2" will be considered further in this report.

"Diatom bed no. 3" is also termed the "Great 400-Foot Marine Miocene Diatomaceous Bed" by Woolman (1895, p. 165-169), and he reported this deposit as occurring both in outcrop and widely distributed in the subsurface of New Jersey. Woolman correlated this with Miocene deposits in Maryland, Virginia, and Delaware, and it is recognized in this report as being the stratigraphic equivalent of Beds 3B through 9 of the Calvert Formation in Maryland and upper Burdigalian to Langhian in age. Woolman (1895, p. 169, 170) reported that his "Diatom bed no. 4" occurred as a distinct stratum in the Wildwood well from depths of 1040 to 1060 feet (317 to 323 m) and was separated from his "bed no. 3" by 247 feet (75 m) of nondiatomaceous strata. He stated that "bed no. 4" was characterized by the occurrence of *Actinoptychus heliopelta*. Woolman's "bed no. 4" is recognized in this report as being the stratigraphic equivalent of Bed 3A of the Calvert Formation in Maryland and of Burdigalian age.

A more comprehensive account of the history of diatom investigations in the Miocene of New Jersey is given in Andrews (1987). That report examines in detail the diatoms from the Atlantic Girl Scout Camp 4 borehole in Atlantic County and correlates the strata according to modern schemes of classification. The youngest Miocene diatomaceous deposit did not occur in the ACGSC-4 well, but the two older Miocene diatomaceous deposits and their stratigraphic correlation are dealt with in detail.

OLDEST DIATOMACEOUS MIOCENE DEPOSIT

The oldest diatomaceous deposit in the Kirkwood Formation of New Jersey is characterized by the following marker diatoms:

Actinoptychus heliopelta

Biddulphia minuta

Raphidodiscus marylandicus

Rhaphoneis fossile

Rhaphoneis margaritata

Sceptroneis caduceus

Trinacria solenoceros

Of these, *Raphidodiscus marylandicus, Rhaphoneis margaritata,* and *Sceptroneis caduceus* are known to range into younger strata, whereas the others are apparently restricted to this bed. The most striking and distinctive of these markers is *Actinoptychus heliopelta,* for which Revised East Coast Diatom Zone 1 of Andrews (1988) is named. The morphology of this species has been studied in detail by Andrews (1979). The oldest diatomaceous bed in the Kirkwood Formation is correlated with Bed 3A of the Fairhaven Member of the Calvert Formation in Maryland as defined by Andrews (1988). It falls within the Burdigalian Stage of Early Miocene age, probably about 18 to 18.5 Ma (see Figure 1). Although it was not recognized by early stratigraphers in Maryland, this deposit is separated from the overlying Miocene strata by a hiatus of from one to two million years. The difference in age is strongly indicated by the distinctive diatom assemblages of the two deposits. The distribution of Bed 3A of the Calvert Formation and its equivalents in the Mid-Atlantic Coastal Plain is shown in Figure 2. The deposit is restricted to southern New Jersey and tapers to a narrow tongue in the central Chesapeake region of Maryland. Deposits of this age have been identified by the writer at the following localities in New Jersey:

1. Atlantic Co., ACGSC-4 well, depth 7301 ft., described by Andrews (1987).
2. Cumberland Co., Shiloh Marl outcrop, near Shiloh,N.J.
3. Cape May Co., artesian well at Wildwood, N.J. described by Woolman (1895, p. 159-170), depth 1045 to 1095 ft.

SECOND DIATOMACEOUS MIOCENE DEPOSIT

The second diatomaceous deposit in the Kirkwood Formation of New Jersey has a much more extensive distribution than the oldest deposit and is characterized by the following marker diatoms:

Delphineis lineata
Delphineis ovata
Raphidodiscus marylandicus
Rhaphoneis fusiformis
Rhaphoneis margaritata
Rhaphoneis scalaris
Sceptroneis caduceus
Sceptroneis grandis
Sceptroneis hungarica

Of these, *Raphidodiscus marylandicus*, *Sceptroneis caduceus*, and *Rhaphoneis margaritata* are known from older strata, and *Delphineis lineata* and *Rhaphoneis fusiformis* are known to range into younger strata. The other species are apparently restricted to this zone. The more abundant and distinctive markers in this zone are *Rhaphoneis scalaris, Delphineis ovata,* and *Rhaphoneis margaritata.* The extinction of *Sceptroneis caduceus* and *Rhaphoneis scalaris* and the first appearance of the two related species, *Sceptroneis grandis* and *S. hungarica,* suggests the possibility of a hitherto unrecognized hiatus within this stratigraphic section.

This middle diatomaceous deposit in the Kirkwood Formation of New Jersey has been assigned to Revised East Coast diatom Zone 2 by Andrews (1988) and is correlated with Bed 3B of the Fairhaven Member and Beds 4-9 of the Plum Point Member of the Calvert Formation in Maryland. It falls within the upper part of the Burdigalian (late Early Miocene) and the lower part of the Langhian Stage (early Middle Miocene) (see Figure 1). The distribution of Bed 3B of the Calvert Formation and its equivalents in the Mid-Atlantic Coastal Plain is shown in Figure 3. The writer has not plotted the distribution of Beds 4-9 of the Calvert formation and their equivalents, but study indicates that their distribution is similar. It can be readily be ascertained from Figure 3 that the deposits of Revised East Coast Diatom Zone 2 have a wider areal distribution than those of Zone 1, both in New Jersey and elsewhere. Deposits of this age have been identified by the writer at the following localities in New Jersey:

1. Atlantic Co., ACGSC-4 well, depth 155-239 ft., described by Andrews (1987).

2. Beach Haven Terrace corehole, well no. 888, depth 250-510 ft.
3. Belleplain State Forest corehole, depth 310 ft.
4. Leed Point corehole, depth 365-425 ft.
5. Surf City corehole, depth 240-450 ft.
6. Atlantic Co., Jobs Point well, depth 376-377 ft.
7. Avalon Boro, Avalon Manor well, depth 600-980 ft.
8. Ocean Co., Island Beach well, depth 120-342 ft.
9. Wildwood, Holly Beach, artesian well described by Woolman (1895, p. 159-180), depth 586-784 ft.
10. Atlantic City artesian well no. 3, southeast corner of Kentucky and Adriatic Aves., described by Woolman (1891, 1892), depth 485-670 ft.
11. Atlantic Co., Egg Harbor Senior High School test well, depth 422-557 ft.
12. Atlantic city offshore well no. 1, 1.9 miles off N. J. coast, water depth 32 ft., depth 510-658 ft.
13. Atlantic City offshore well no. 2, water depth 43 ft. depth 794-819 ft.
14. Burlington Co., Manahawkin corehole, depth 140 ft.
15. Cumberland Co., Belleplain test well, depth 368 ft.

YOUNGEST DIATOMACEOUS MIOCENE DEPOSIT

The youngest diatomaceous Miocene deposit in the Kirkwood Formation of New Jersey is characterized by the following marker diatoms:

Actinoptychus marylandicus

Actinoptychus virginicus

Delphineis angustata

Delphineis biseriata

Delphineis novaecaesaraea

Delphineis penelliptica

Denticula hustedtii

Lancineis clavata

Lancineis lancettula

Lancineis parilis

Rhaphoneis amphiceros

Rhaphoneis gemmifera

Rhaphoneis rhombica

Rhaphoneis scutula

Thalassiosira grunowii

These marker species are distinctive from those in the oldest and second diatomaceous deposits in New Jersey. The beds classified as "Revised East Coast Diatom Zone 3-4" in Maryland are missing in New Jersey and are followed by a hiatus of slightly over one million years in Miocene sedimentation in New Jersey. Thus there is effectively a hiatus in the Miocene of about two million years between the second and the youngest diatomaceous deposits in New Jersey.

The youngest diatomaceous deposit in the Kirkwood Formation of New Jersey has been assigned to Revised East Coast Diatom Zone 6 by Andrews (1988) and is correlated with Beds 15 and 16 of the Calvert Beach Member of the Calvert

Formation in Maryland. This diatom zone falls slightly below the middle of the Serravallian Stage of Middle Miocene age and is dated at approximately 13-14 Ma. It is also partially equivalent to Planktonic Foraminifera Zone N11 and Calcareous Nannofossil Zone NN6 (Andrews, 1988, Fig. 1). The distribution of deposits of this age in the Mid-Atlantic Coastal Plain has not been plotted. However, beds of this age have a widespread distribution in the Maryland-Virginia-Delaware area as well as in southern New Jersey, which suggests a major marine transgression during this period of Miocene time. Deposits of this age have been identified at the following localities in New Jersey:

1. Belleplain State Forest corehole, depth 220-240 ft.
2. Leed Point corehole, depth 236 ft.
3. Atlantic Co., FAA test well, Pomona, N. J., depth 245 ft.
4. Cape May Co., Avalon Manor well, Avalon Boro, depth 340-342 ft.
5. Cumberland Co., well near Heislerville, depth 120-125 ft.
6. Atlantic Co., Stockton College test well, Nacote Creek and Garden State Parkway, depth 225 ft.
7. Cape May Co., artesian well at Wildwood, N. J. on Holly Beach, 7 miles north of Cape May, described by Woolman (1895), depth 428-535 ft.

8. Atlantic City artesian well no. 3, southeast corner of Kentucky and Adriatic Aves., described by Woolman (1891, 1892), depth 382-470 ft.
9. Atlantic Co.,Egg Harbor Senior High School test well, depth 152-285 ft.
10. Cumberland Co., Auger hole no. 8, northeast corner of Fortescue, parking lot of Higbee's Marina, depth 42-44 ft.
11. Atlantic City offshore well no. 1, 1.9 miles off N. J. coast, water depth 32 ft., depth 424-465.7 ft.
12. Atlantic City offshore well no. 2, water depth 43 ft., depth 568-658 ft.
13. Atlantic Co., Margate test well, intersection of Margate and Burk Ave., depth 390 ft.

CONCLUDING STATEMENT

Much of the research on the Miocene diatoms of New Jersey was done during the writer's employment with the Branch of Paleontology and Stratigraphy, U. S. Geological Survey, Washington, D. C. and Reston, Va., from 1981 to 1989. Additional support for this study was obtained from a grant by the New Jersey Geological Survey. Samples were primarily supplied by James P. Owens, USGS, and Peter J. Sugarman, New Jersey Geological Survey. The writer is indebted to them for many helpful discussions on New Jersey Miocene stratigraphy.

The illustrations accompanying this report are taken from a paper entitled "Silicoflagellate and Diatom Biostratigraphy in Successive Burdigalian Transgressions, Middle Atlantic Coastal Plain" by Wetmore and Andrews (1990). That report provides a study specifically on the Early Miocene strata of the middle Atlantic Coastal Plain, as well as illustrations of important marker diatoms and silicoflagellates. For a regional treatment of Miocene diatom biostratigraphy of the southeastern United States, the reader is referred to Andrews (1988), which also contains systematic descriptions and illustrations of marker diatoms. A discussion of Miocene stratigraphy and diatom biostratigraphy of New Jersey is found in Andrews (1987).

The data in this report on the occurrence of the various Miocene diatom zones in New Jersey wells is inclusive and shows only the range in depth of observed samples. Such depth ranges do not indicate a continuous diatomaceous section from top to bottom, but only that diatoms of a given age have been observed at and between these levels. It has been impossible within this format to provide detailed data on all of the well samples and outcrops studied. However, it is hoped that this summary report will provide useful information on the distribution and occurrence of Miocene diatomacous deposits in New Jersey.

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FIGURE CAPTIONS

Figure 1. Correlation of revised East Coast Diatom Zones of Andrews (1988) with other fossil zonations. Column 1 shows planktonic foraminifera zones, and column 2 shows calcareous nannofossil zones. (From Wetmore and Andrews, 1990, p. 284).

Figure 2. Areal extent of Bed 3A of the Calvert Formation in Maryland and its equivalent in the Kirkwood Formation of New Jersey. (From Wetmore and Andrews, 1990, p. 285).

Figure 3. Areal extent of Bed 3B of the Calvert Formation in Maryland and its equivalents in the Mid-Atlantic Coastal Plain, including New Jersey. (From Wetmore and Andrews, 1990, p. 286).

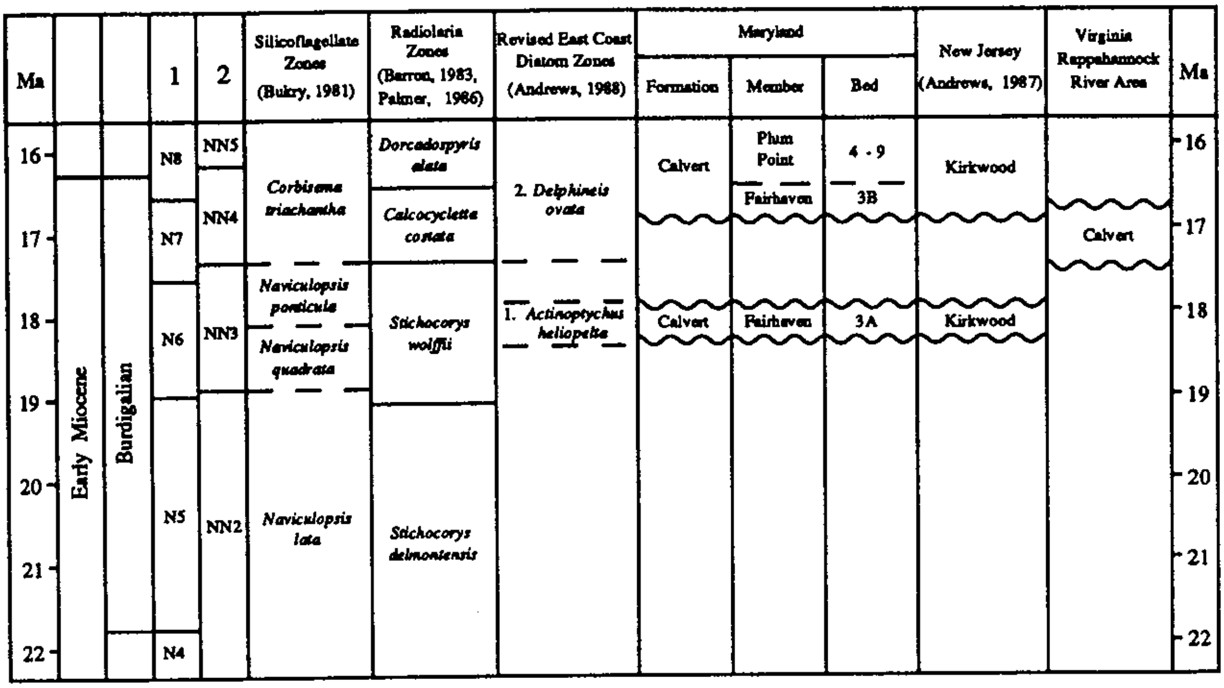

Figure 1. Correlation of revised East Coast Diatom Zones of Andrews (1988) with other fossil zonations. Column 1 shows planktonic foraminifera zones, and column 2 shows calcareous nannofossil zones. (From Wetmore and Andrews, 1990, p. 284).

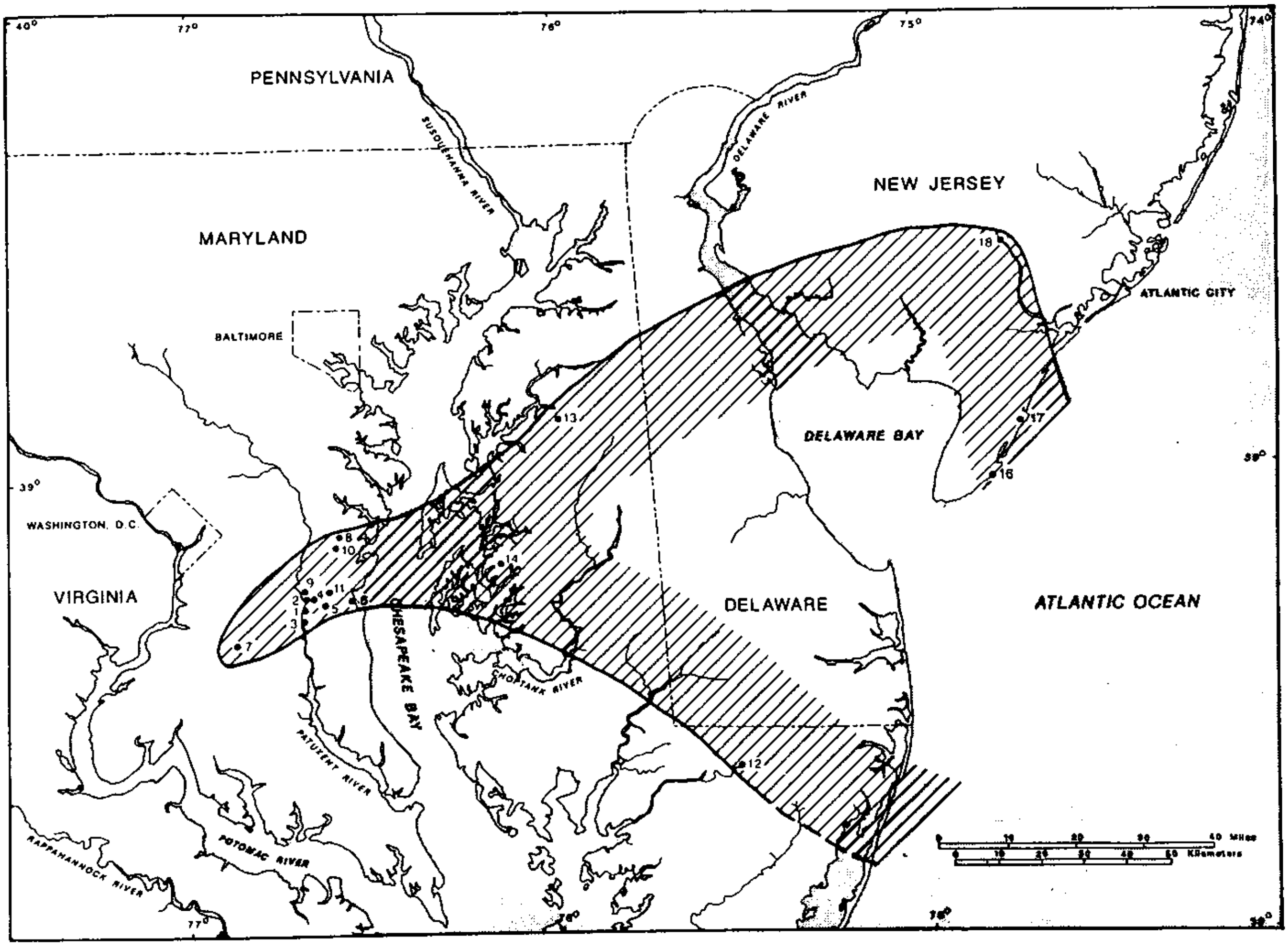

Figure 2. Areal extent of Bed 3A of the Calvert Formation in Maryland and its equivalent in the Kirkwood Formation of New Jersey. (From Wetmore and Andrews, 1990, p. 285).

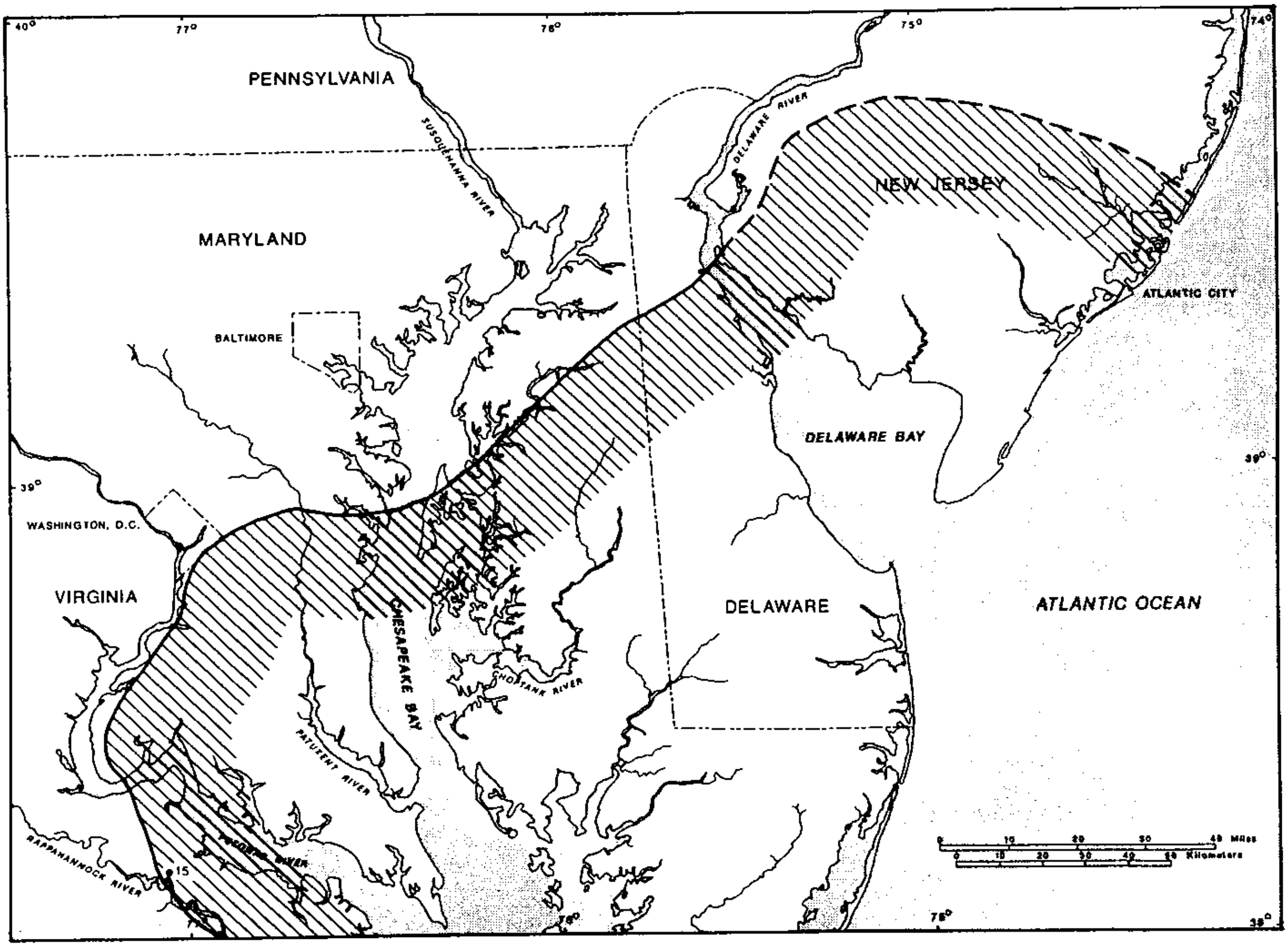

Figure 3. Areal extent of Bed 3B of the Calvert Formation in Maryland and its equivalents in the Mid-Atlantic Coastal Plain, including New Jersey. (From Wetmore and Andrews, 1990, p. 286).

SIMPLE METHODS FOR EXTRACTING MICROFOSSILS OF THE NAVESINK FORMATION (CRETACEOUS; N.J.)

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INTRODUCTION

Knowledge of the basic principles and concepts of earth history are important in the general earth science curriculum of or secondary schools. A field trip to the Cretaceous sediment outcrops in New Jersey's Coastal Plain is a perfect chance to introduce to many earth science teachers the field of micropaleontology. The microfossils can be collected easily, and in vast numbers, by the members of a field trip, and can be used to demonstrate many principles studied in the earth history section of the earth science curriculum; for example: stratigraphy, biostratigraphy, paleoecology, sedimentation, geologic correlation, evolution, marine environment, plate tectonics, paleotemperature, paleodepth, etc. It is hoped that this paper will help "orient" the interested instructor in this unique, fascinating and evermore important branch of the earth sciences. Much has been written about the great significance of microfossils used by the Deep Sea Drilling Project (and its ship, the "Glomar Challenger") to enhance our knowledge of sea-floor-spreading and plate tectonics. Many of these organisms can be found in the sediments of New Jersey.

PROCESSING SEDIMENTS FOR MICROFOSSIL RETRIEVAL

1) Take a sample of Navesink fm. glauconitic sediment from the bank of the stream - you must collect a fresh sample (approx. 1 qt. or 1 L.) by digging laterally six inches. Place sample in plastic bag or jar. You now have several thousand microfossils, several million if you count the nannofossils.

2) To a smaller sample (subunit) add some water and hydrogen peroxide ($H2O2$) and allow to fizz for 25-30 minutes or until sediment is completely unconsolidated. One pint of hydrogen peroxide per quart of sample is a general rule of thumb. Stir with hand to help break up sediment.

3) Pour and wash through "nested" sieve set using a steady, light stream of water (a garden hose will do.) Separate sieves and do the same with each one individually.

4) Allow sediment to dry in screens in the sun, and place each sample in a separate container. The middle fractions will yield the larger microfossils (benthonic forams and ostracodes.) The smallest fractions contain planktonic forams.

5) "Pick" microfossils with a moist "00000" sable brush under a 30-40X binocular "dissecting" microscope. The lighter-colored microfossils stand-out nicely against the

dark green of the glauconite sand. Place microfossils on a standard micropaleontology slide (see a Ward's catalog) smeared with a dilute Elmer's glue solution which has dried; this will allow the specimens to remain in place.

HISTORY OF MICROFOSSIL STUDIES OF THE NAVESINK FORMATION

Bagg (1898) was the first to describe foraminifera of the Late Cretaceous formations of New Jersey in an article published with Weller's (1907) volume on the Cretaceous of New Jersey. Brady's (1884) volume on the foraminifera recovered from the voyage of the H.M.S. "Challenger" was Bagg's main source and consequently he considered many of the Cretaceous species to be the same as modern species. Jennings (1936) presented a more complete and updated description of the foraminifera and ostracodes of the Cretaceous of New jersey. Olsson (1960) revived the study of foraminifera in the State and has sustained the interest from a biostratigraphic and paleoecologic point of view. Many of his students have also made contributions to the study of the microfauna of the Cretaceous of New Jersey and, more recently, the sediments of this age in the State have been dated and correlated with world-wide planktonic foraminiferal biostratigraphic zones. More recent studies using newer, deeper cores have resulted in many refinements. Many of these are summarized in this symposium volume.

THE MICROFOSSILS

Knowledge of the Cretaceous and Tertiary strata of New Jersey has been consistently improved by contributions in the field of micropaleontology (the study of fossils more adequately examined with a microscope.) These microorganism remains are so useful because they are so numerous, well preserved and many have world-wide distribution allowing correlation between other geographic areas whose strata were deposited at similar ages and under similar conditions. The following list of microfossils found in the Navesink Formation of the Cretaceous of New Jersey gives a brief account of their significance, taxonomic position, structure and composition.

1. FORAMINIFERA: These organisms are unicellular, amoeboid protozoans who secrete a "shell" or test of calcium carbonate, or sand grains cemented by calcium carbonate. Ecologically, they have a planktonic (floating) or benthonic (bottom-dwelling) habit; examples of both are present in great numbers in the Navesink formation. The "forams" are one of the most common and important microfossils in this formation. See below for more detail.

2. OSTRACODES: The carapace of these tiny, mostly benthic, bivalved crustaceans are also quite numerous in the Navesink Fm. They also have a calcium carbonate composition. Next to the forams, they are the second most common large microfossils in the Navesink Fm.

3. DINOFLAGELLATES: These tiny, unicellular, planktonic flagellates produce a cyst in their life cycle whose "theca" (a sporopollenin protein covering) is preserved in the sediment of the Navesink Fm. They are becoming more

important in biostratgraphic studies throughout the world. Unfortunately, the method of retrieving these microfossils is more complicated than normal and cannot be discussed here.

4. FISH REMAINS: The bones of herring-sized fish and their teeth will be found in your preparations; they are yellowish to dark brown.

5. FECAL PELLETS: These greenish, extremely smooth, oval particles are fossilized fecal remains of gastropods or echinoids. They are fairly common (Boyer, et. al. 1977.)

6. ECHINOID SPINES: The "glassy" spines of sea urchins will also be common microfossils in the preparations.

7. CALCAREOUS NANNOFOSSILS: If one takes a small sample of Navesink formation material (1 ccm) and dissolves it in water and then places a drop of the supernatant on a slide with a coverslip and examines under the oil immersion lens (1000X), one will see a myriad of extremely small "discs", "clubs" and "crosses." These as the coccoliths (class Haptophyceae.) Biostratigraphically, these are an extremely important group of microfossils; they are made of CaCo3 and are best studied with an S.E.M.

FORAMINIFERA

The "forams" are the most important group of microfossils. They consist of 3 basic forms (suborders) based on the composition of their test or shell. The "miliolinids" have a non-porous (imperforate), porcelaneous test that is white and shiny, usually with one aperture; these are uncommon in the Navesink formation. The "rotaliids" are the most common forms in the Navesink Fm. and have a porous "microcrystalline" test structure; the "planktonic" forams are in this group, as are many of the "benthonics" (bottom dwellers.) These two suborders have tests that are made of calcium carbonate. The most primitive group is the "textulariids" which have foreign material cemented together as a test, usually sand grains cemented by calcium carbonate. The animal that secretes these beautiful tests ia an amoeba, so the tests are protozoan shells. Geologic range is Cambrian to Recent. Two other suborders are not considered here: fusulinids and allogromiids.

There are several basic structures common to the three groups above. If the animal secretes only one chamber it is termed "unilocular",; if more than one it is "multilocular." When the multilocular forams arrange their chambers in a single row it is termed 'uniserial"; whereas two would be "biserial"; three would be "triserial". There can be combinations, as in the case of triserial form becoming uniserial in the later stages of growth. "Trochospiral" forams have coiled tests, as in a common snail; "planispiral" forams coil in a single plane, as in the chambered Nautilus. The line marking the border between chambers is called a 'suture."

The "aperture" is the main opening out of which the protoplasm flows; it is usually visible only on the last chamber formed; it may be "radiate" or have a "tooth"; a "keel" may also be present.

The foraminifera have many other "ornaments", such as spines; ribs called "costae"; "lips" around the aperture; an indentation on one side of the trochospiral forms called an "umbilicus", etc.

NAVESINK FORMATION PALEODEPTH DETERMINATION: AN EXAMPLE OF MICROFOSSILS IN PALEOECOLOGICAL ANALYSIS

Benthic and planktic foraminifera can be used to determine many ecological parameters of ancient environments, including temperature, currents, depth, turbidity, salinity, proximity to shoreline, etc. We will consider "paleodepth" (paleobathymetry) here as an example of such studies. The Navesink formation is considered to have been deposited in the outer neritic or outer shelf zone (continental shelf.) This determination has come about through the use of more general studies of modern habitats of certain foram taxa, their overall distribution, ratios of planktic to benthic forams, recurrent associations and homeomorphic comparisons. Olsson (1977) devised a model for determining paleodepth for the Campanian - Maestrichtian (uppermost Cretaceous) in the western Atlantic borderlands. Generally, outer shelf assemblages have increased species diversity (many species) and up to 50% planktic forams; glauconite and fine grained sediments (clay sized) are also characteristic. Olsson further determined that the inner shelf assemblage for this time period would include, among others, Globulina lacrima, Guttulina sp., the outer shelf assemblage would include lagenids (e.g., Lagena adepta), Coryphostoma plaitum, Clavulina trilaterus and Anomalinoides pinguis; the bathyal (slope) would include Clavulina trilaterus also, and Gaudryina laevigata. Since our Navesink formation samples from the Poricy Brook local includes all these and are also rich in clay and glauconite, and forthermore, have good species diversity, a large number of planktic forams (close to 50%), we can conclude that the Navesink is indeed classified as being of outer shelf deposition by the following interpolation: it is unlikely that an inner shelf assemblage would have bathyal forms, and that a bathyal assemblage would have inner shelf forms, but an outer shelf assemblage would have some elements of the other two.

GOOD LUCK!

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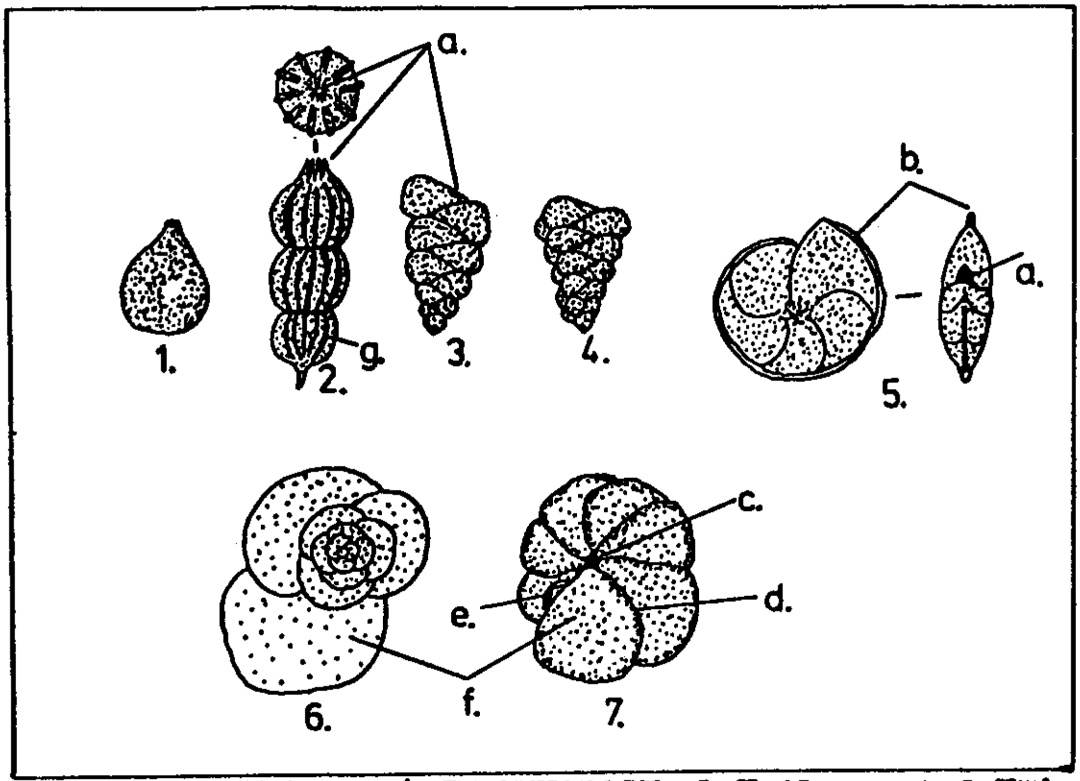
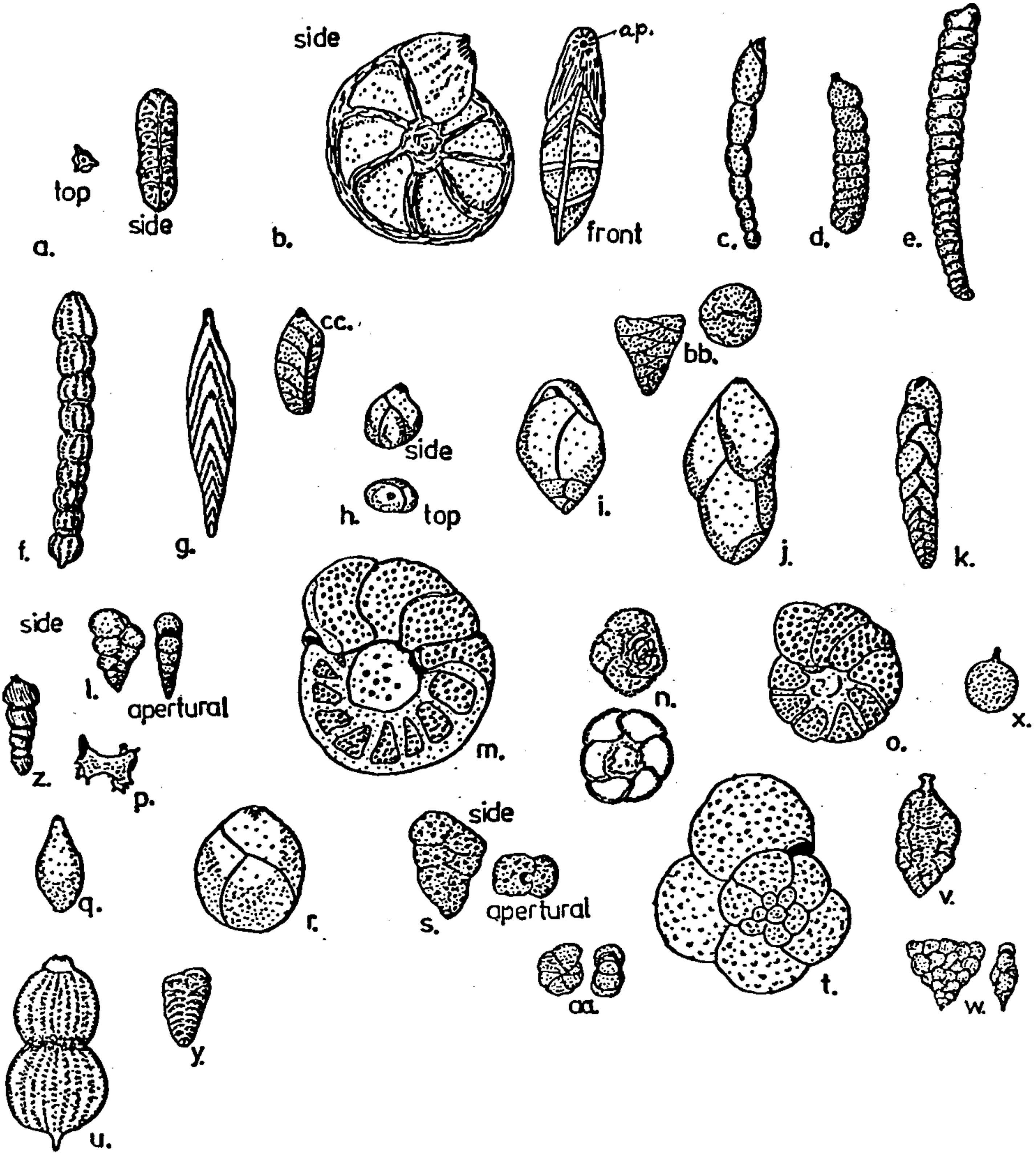


Fig. 1. FORAMINIFERA TERMINOLOGY: 1.Unilocular, 2.Uniserial, 3.Biserial, 4.Triserial, 5.Planispiral, 6.Trochospiral-spiral side, 7.Trochospiral-umbilical side. a.apertures, b.keel, c.umbilicus, d.suture, e.lip, f.chamber, g.costae.

Poricy Forams ✱ = PLANKTONIC

No.	Genus,	Max. Length: mm
a.	Clavulina	1.9mm
b.	Lenticulina	1.7mm
c.	Dentalina	1.2mm
d.	Marginulina	1.3mm
e.	Vaginulina	2.1mm
f.	Nodosaria	2.4mm
g.	Frondicularia	2.0mm
h.	Globulina	1.0mm
i.	Bulimina	0.2mm
j.	Guttulina	0.7mm
k.	Coryphostoma	0.9mm
l. ✱	Heterohelix	0.3mm
m.	Cibicides	0.4mm
n. ✱	Globotruncana	0.5mm
o.	Anomalinoides	0.5mm
p.	Ramulina	1.0mm
q.	Lagena	0.7mm
r.	Same as "h." above	-
s.	Gaudryina	0.3mm
t. ✱	"Globigerina"	0.1mm
u.	Nodosaria	0.5mm
v.	Pseudouvigerina	0.3mm
w. ✱	"Platystaphyla"	0.7mm
x.	Lagena	0.5mm
y.	Spiroplectammina	0.3mm
z.	Dentalina	1.5mm
aa.	Pullenia	0.5mm
bb.	Textulariella	.7mm
cc.	Saracenaria	1.0mm


side
a.p.
top
side
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e.
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side
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l.
apertural
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Techniques useful for the breakdown of indurated Paleozoic Rocks in New Jersey and for the Separation of various microfossil groups from the resulting insoluble residues

Dr. Barry Perlmutter, Geoscience/Geography Dept., Jersey City State College

The following procedures are extremely helpful in the breakdown of various rock types including: limestone, various shale types, sandstone and chert. They are either used alone or in a sequential combination with one of the other techniques, when simpler techniques such as boiling the samples in water fail to produce the desired results.

Other procedures are useful afterwards when sieved insoluble residues are large to concentrate various microfossil groups including: Foraminifera, Ostracodes, conodonts, Scolecodonts, Radiolarians, bone fragments and pollen. Such other procedures reduce examination and picking time of the residues considerably.

Both sets of procedures have an added bonus, in that, many of the materials used are cheap, safe, and easy to obtain (some are even supermarket products such as Liquid Plumr, Dawn and the gum tragacanth powder used as a water-soluble glue for mounting the microfossils). Some of the other materials used, such as Stoddard's Solvent and Sodium Metatungstate, can be recycled many times for cost effectiveness. It should be noted that some procedures require expensive equipment (such as the Franz Electromagnetic Separator) or involve safety issues (when using Hydrofluoric, Formic or Acetic Acids).

Among the rock breakdown techniques are: The digestion of limestones using Acetic or Formic Acids (Collinson,1963) to recover silicic or phosphatic microfossils, use of Stoddard's Solvent (or other similar dry-cleaning fluid) to sludge clay shales (Collinson,1963, Mapes and Mapes,1982), the use of drain Cleaner in processing organic black shales (Maples and Waters, 1990), the use of Quaternary 'O' for disaggregating hard shales and argillaceous sandstones (Zingula,1968, Duffield and Warshauer,1979), and the use of Hydrofluoric acid to process chert and other silicic rocks (Orchard,1987).

Concentration techniques include: Electromagnetic Separation (Dow,1960) to concentrate phosphatic material, sodium metatungstate heavy liquid separation (Krukowski, 1988), Interfacial separation techniques using the interfacial trapping of phosphatic particles between water and kerosene-paraffin(Freeman,1982, Merrill,1985).

Laboratory Techniques for digesting Limestones, Calcareous Shales and Calcareous Siltstones to recover non-calcareous microfossils

Procedure

1. Wash the sample thoroughly.

2. Crush the sample manually or with a rock crusher to walnut-sized chunks.

3. Weigh approximately 500 grams of the sample.

4. Place this amount in a plastic pail.

5. Add 3/4 qt. Industrial grade Formic Acid to 6 1/4 qts. water and let stand no more than 24 hours to prevent etching (if Acetic Acid is used instead, the sample can stand for up to three days before etching begins).

6. Use a top sieve of 10 or 20 mesh and a bottom sieve of 100-140 mesh and wash thoroughly. Recycle the sample in repeat of Step 5 if all sample is not digested.

7. Residue remaining on bottom sieve contains silicified, chitinous, or phosphatic microfossils and should be decanted into beaker or paper towel and put into an oven to dry. Residue can be concentrated using technique described in section illustrating the removal of Phosphatic microfossil fragments or other concentration techniques such as magnetic separation.

Laboratory techniques for breakdown and concentration of shales, siltstones, and mudstones

The aim of these procedures is to soften and "sludge" these types of rocks so they may be washed through sieves to begin concentrating the residues, which frequently contain microfossils such as foraminifera, radiolaria, ostracodes, conodonts and other types,which can be observed with low-powered microscopes. The technique makes use of a dry-cleaning fluid, Stoddard's Solvent, which causes any clay present in the rock to swell. The solvent is safe to use, has very little odor, can be poured over sample removed after drying in an oven at 400 degrees F.with no danger of flammability and is cheap and easy to obtain. It can be recycled after each use by pouring back through a filter which removes sediment.

Procedure

1. Place sample in a metal container the size of a 1 lb. coffee can (filling just below the top is the optimum- sized sample- about 500 grams).

2. For the deepest penetration of the solvent, warming or heating the sample is necessary in an oven no more than 400 degrees F. for about an hour or over a Bunsen Burner.

3. Pour Stoddard's Solvent over sample until it is covered and let stand for about 30 minutes.

4. Pour back the solvent through a funnel lined with filter paper.

5. Add water immediately and allow sample to stand 2-24 hours to sludge.

6. If sample has only partially sludged, pour off water and repeat steps 2-5.

7. Wash the sludged sample through two stacked wet sieves,using a top sieve of standard series number 20 to remove any large remaining chunks and a bottom sieve of standard series number 100 or 120 to capture the residue containing the microfossils. Any additional matrix washes down the sink.

8. Residue on the bottom sieve can be washed into a beaker, the water poured off and the sample air dried or dried by heating.

9. The residue can be picked using an artist's "0" brush.

10. Samples can be mounted on standard gridded micro- slides using a water soluble glue made from Gum Tragacanth powder.

Laboratory technique utilizing Drain Cleaner in processing Organic Shale Samples

Procedure

1. Dry sample in oven for one to several hours.

2. Soak the sample in Stoddard's Solvent for 24 hours.

3. Wash the sample thoroughly and dry again..

4. Soak the material in Liquid-plumr for 24 hours (this brand is recommended because it contains one of the strongest concentrations of sodium hypochlorite and sodium hydroxide). If other brands are used, check ingredients since some are just concentrated Sulfuric acid.

5. Sieve the samples after steps 1-4 are repeated several times.

6. If a thin clay coating remains around the fossils, one additional Stoddard's soak may be necessary.

The use of Quaternary 'O' for disaggregation of hard shales, argillaceous sandstones or limestones

Quaternary 'O' is a tertiary amine compound marketed by Ciba-Geigy in the U.S.A. It is used as a detergent with good wetting properties.

Procedure

1. Boil water containing the sample.

2. Make a 20 % solution of Quaternary 'O' using warm water.

3. Add this to the boiling water with sample.

4. Using a hot plate, keep the mixture boiling until the sample breaks down, stirring to prevent sticking and froth buildup under a fume hood to remove odor.

Using Hydrofluoric acid (HF) to process Chert and other siliceous rocks

Procedure

1. Remove any carbonate by digestion in Formic or Acetic acids.

2. Crush 200 g. of the siliceous materials in 1-5 cm. fragments.

3. Place fragments into a plastic beaker of 5-6% HF under a fume hood (no more than one-half full beaker to allow for frothing).

4. Decant the HF and wash sample in dilute Hydrochloric Acid.

5. Decant the HCl and replace with water until the liquid remaining is neutralized.

6. Sieve and return undigested material for further breakdown.

Electromagnetic separation of phosphatic microfossils

A Franz Electromagnetic separator (The Franz Co. is located in Trenton, N.J.) consists of a powerful adjustable electromagnet and an inclined, vibrating chute, divided into two channels (the chute front and side slope angles are adjustable). The chutes separate out the ferromagnetic components (limonite and hematite usually) from the residue remainder (including phosphatic components).

Procedure

1. Set the inward side slope angle at 5-10 degrees, the forward slope angle between 20 and 30 degrees, turn on the vibrator and set the initial amperage between 0.6 and 1.0.

2. Feed the residue through the funnel slowly and allow it to run down the chute as a single stream of particles.

3. The inner channel contains "non-magnetic" components, usually phosphatic, quartz and dolomitic particles, outer channel contains ferromagnetic components.

4. Run a second time to achieve a more complete separation.

5. Any significant quartz or dolomite components can be removed later by heavy liquid separation (e.g. Sodium metatungstate).

A technique for removing phosphatic microfossil fragments (such as vertebrate and conodont remains) from larger samples of rock such as unconsolidated sandstone samples.

This technique takes advantage of the fact that calcium phosphate particles selectively attract oils to their surfaces. In the most practical form of the procedure, these oil coated grains can then be made to adhere to the surfaces of materials ('substrates") for which oil is a solvent. The technique uses locally available products such as Dawn(Proctor&Gamble) or Palmolive Dishwashing Liquid (Colgate-Palmolive Co.) to act as an emulsifier for an oil solvent like Varsol or Kerosene(used in very small amounts) and paraffin flakes (used as the substrate). The technique is great because it safe, efficient, fast and cheap(about 10 cents per average run).

Procedure

1. The sample is spread across the bottom of a shallow , flat, enamelled pan (approximately 25X 40X 5 cm.).

2. Cover with detergent solution (1 part Dawn to 99 parts water) to a depth of roughly 1/2 cm..

3. Add about 5ml. of oil based solvent (which would be very effective) and agitate to disperse the solvent into tiny droplets.

4. Add thin flakes of paraffin wax to to the pan (a handful of flakes with ideal sizes of 1-2 cm. long and 2 mm. thick) and agitate again.

The oil-coated, phosphatic particles adhere to the wax flakes preferentially and can be skimmed off and collected in a beaker. Three or four repetitions should remove all the phosphatic particles from the sample.

5. After collecting wax flakes, additional detergent solution is added to the beaker of flakes.

6. Heat the solution and wax flakes on a hot plate until the wax melts and stir. The melted wax helps disperse and emulsify any oil droplets remaining . The phosphatic particles fall to bottom of beaker.

Sodium Metatungstate Heavy mineral separation technique for the removal of phosphatic microfossils from insoluble residues

Sodium Metatungstate (SMT) is a non toxic, high density compound (up to 3.10 density) used effectively to remove large platform conodonts and bone material from insoluble residues. It replaces toxic and carcinogenic heavy liquids formerly used, such as, Bromoform and Tetrabromoethane with specific gravities of 2.89 and 2.96 respectively. While its water solubility makes maintenance of constant density difficult, it is recyclable up to 200 times, and in addition to being non toxic it is non corrosive and presents no fire hazard. It is available only from Sometu in Berlin,Germany (although a similar material - Sodium Polytungstate is available in the U.S. from Geoliquids Co., Prospect Heights, Illinois). The cost is now likely to be $100/lb. for the powder. The only limitation is the preferential use of plastic ware over glassware to prevent adherence of the SMT salt to the sides of the glass funnel, which can be flaked rather than washed off plastic.

Procedure

1. Mix SMT powder with distilled water (4 kg. of powder yields 5 kg. of solution at a density of 2.90 which fill about three or four moderate sized funnels).

2. Fill plastic separatory funnel with 200-300 ml. of SMT liquid, 15 cm. high.

3. Place residue in funnel and stir gently every three hours. The funnel should be covered with plastic wrap to prevent evaporation and maintain density.

4. After nine to twelve hours, heavy mineral fraction should be drained into a filter funnel. Also drain light fraction into a filter (coffee filters are cheaper and have faster flow rates).

5. Rinse residues with distilled water and allow them to dry overnight.

6. Save heavy liquid filtrate and reuse. Check density regularly with a mineral crystal of known density or a predetermined density chip.

7. Filter cloudy heavy liquid every five to ten samples to remove clay-sized suspended particles.

8. After use of filter paper, rinse one or two times to collect any dry SMT.

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Paleozoic Stop 1.

CLINTON BLOCK AND SUPPLY SITE

This large quarry operation reveals some new information about the puzzling Jutland sequence, long a source of geologic dispute. We have received gracious permission from the company for this visit and you may feel free to seek specimens while here. However, it is not open to casual visits and collecting. We ask that you respect the company's operations and equipment, of course.

The Jutland sequence was once attributed to the Martinsburg Formation, but this is no longer considered appropriate. It has not yet been given new formational nomenclature to our knowledge. Work on this site by Markewicz, Dalton, Monteverde, Volkert, and others of the New Jersey Geological Survey has proceeded over a number of years. Current paleontological study by Parris, Miller, and Finney (this volume) was suggested by the NJGS and is well underway.

Although the surfaces change daily in this active quarry, we will attempt to show the various levels from which graptolites are found in this largely clastic sequence. Of particular interest are the bentonites visible in the quarry face. Graptolites and conodonts may be found here; we expect that this visit may reveal some new collecting levels.

STOP 2 - THE WILLIAM NEARPASS QUARRY

Leader: Shirley S. Albright, The New Jersey State Museum

Directions: Proceed north on Route 206 from Culver's Gap, New Jersey. Just before the Delaware River tollbridge to Milford, Pennsylvania, bear right onto Clove Road (Route 653). Go 6.1 miles north on Clove Road which parallels the Wallpack Ridge. The exposures occur on your left, approximately .5 miles from the parking area, along the eastern flank, crest and secondary rise of the Wallpack Ridge. Visitors must obtain permission from the property owners.

Safety Precautions: The ridge is quite steep in places. Please exercise caution as you collect. Call out to people below if you inadvertently dislodge rock. Hard hats are recommended, especially when large groups are visiting.

Discussion:

Nine formations are visible at this stop, making it one of the most extensive Silurian-Devonian sequences in New Jersey. The quarry is also the type section for the Clove Brook Member of the Decker Formation (named for Clove Brook which flows just northeast of the site) and the Duttonville and Mashipacong Members of the Rondout Formation. Future access to the quarry is threatened by widespread residential development along the ridge, particularly to the south.

The formations, listed in stratigraphic order from the base up, as reported by various authors (Weller 1899, Herpers 1952, Barnett III 1966, Spink 1967, and Epstein et al 1967) are:

Bossardville Formation	9	feet
Decker Formation, Clove Brook Member	42.7	
Rondout Formation, all Members	50.5	
Manlius Formation, Thacher Member	34.8	
Coeymans Formation, Shawnee Island Member	29	
Kalkberg Formation	37	
New Scotland Formation (covered)	112	
Minisink Formation	21	
Port Ewen Formation (covered)	160	
Oriskany Group, Glenerie Formation	177	
Esopus Formation	105	
TOTAL	788	feet

Footages include both exposed and covered portions.

Fossils have been reported from the Minisink, Kalkberg, Coeymans, Manlius, Rondout, and Bossardville Formations at this stop. You can expect to find stropheodontid and spiriferid brachiopods, tentaculitids, stromatoporoids, leperditid ostracods, rugose and favositid corals, and pelmatozoan plates and columnals.

No conulariids have been collected here, but they have been found in the Port Ewen, Marcellus and Esopus Formations exposed in the Wallpack Ridge further south in Sussex County, New Jersey (Herpers 1949, Albright 1995). It is not inconceivable they could be found here also. Additionally, other marine fauna have been found within discrete lenses and as isolated individuals within the Esopus (Parris and Albright 1980). Complete prospecting of the Esopus has been lacking due to summary dismissal by early investigators - probably due to the relative inaccessibility of the unit and the general paucity of fossil material in comparison with adjacent rocks.

The exact location of the Silurian-Devonian boundary at the William Nearpass Quarry remains controversial. Interpretations based upon conodont analysis (Epstein et al. 1967) suggest the boundary lies at the top of the Thacher Member: that is, between the Manlius and Coeymans Formations. However, many authors place the boundary even lower in the section - at the base of the Manlius (Weller 1903, Wagenhoffer 1977) or within the Whiteport Member of the Rondout (Barnett III 1970).

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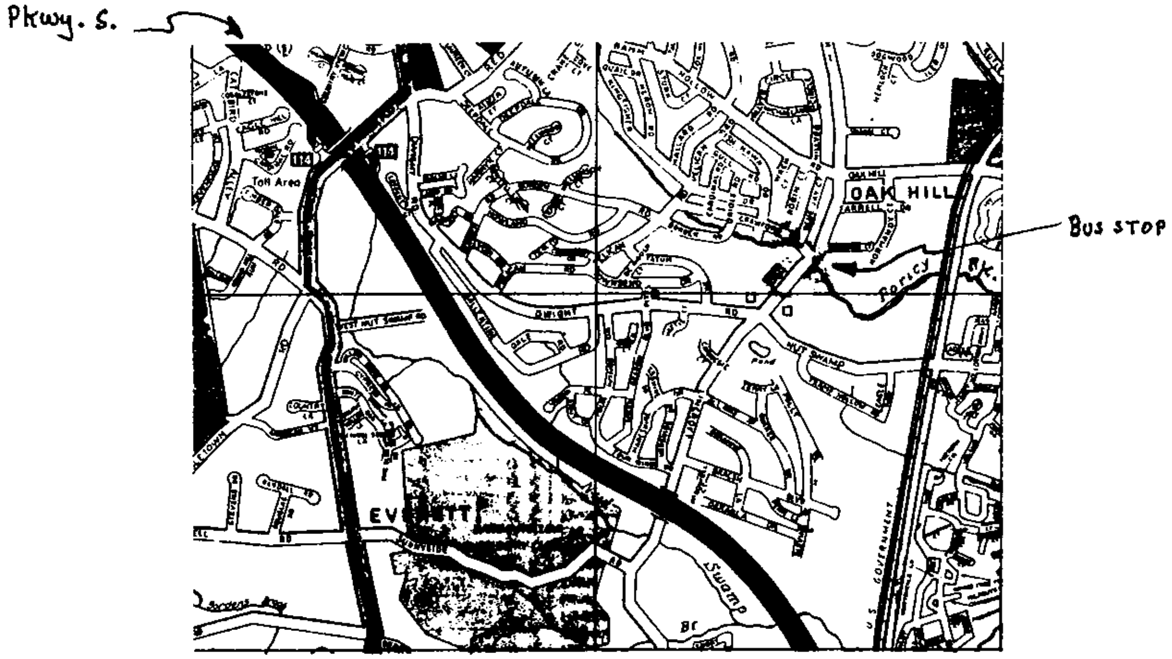
MICROFOSSIL FIELD STOP
LATEST CRETACEOUS (MAESTRICHTIAN)
NAVESINK FM. PORICY BROOK
AT MIDDLETOWN-LINCROFT RD., MIDDLETOWN, N.J.



From Exit 114 on N.J. Parkway take Red Hill Rd. north to 2nd light (Dwight Rd.) and make a right. Go approximately 2 miles to light and make left on Middletown-Lincroft Rd.; Go 0.2 miles over Poricy Brook and park in assigned area on right. Head South and East by foot about 125 feet and enter stream across from large cut bank facing you. Top and Left (East) is Red Bank Formation. Head West upstream and for the next several hundred yards you will pass down through the Transgressive-Glauconite/Chalky Navesink Formation of a mid to outer shelf depositional environment. Slow deposition produced a stratum only 40 feet thick, now dipping gently seaward. The purpose of this stop is to collect material for Microfossil Extraction (See Baker, "Teacher Workshop", in this volume). At the lowest portion of the formation there is a Pycnodonte convexa bed ("Oyster Reef") which is, of course, upstream. Common macrofossils that will be encountered are Exogyra, Pycnodonte, Agerostrea, Belemnitella, Cliona, and Choristothyris. Microscopic examination and thin section analysis of sieved Glauconite grains show their botryoidal shape with numerous cracks filled with pyrite framboid clusters; under SEM almost all the "clay" appears to be coccoliths (calcareous nannofossils or nannoliths of unicellular planktonic algae, see Bybell, Self-Trail, this volume). The large occurrence of nannofossils plus coarse glauconite grains riddled with pyrite framboids attest to an exceedingly slow accumulation rate and low oxidation rate. Both planktonic and benthonic forams are extremely common, the former having equal biostratigraphic value with the nannofossils. Ostracodes are very common also (see Gohn, this volume).

Samples for microfossils should be collected by hammer on cut banks of meanders. You will be well rewarded.

Paleontology and Stratigraphy of the Inversand Pit, Gloucester County,N.J.

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Stop 2, Coastal Plain Field Trip
Geological Association of New Jersey Annual Meeting

Introduction

The Inversand Pit represents the last surviving example of an industry that was once widespread in the marl belt of the Inner Coastal Plain of New Jersey. Mined as fertilizer in the nineteenth century, today greensand marl is dug at this site for use as a municipal water conditioner because of the high ion exchange capacity of glauconite. During the heyday of the marl mining industry in New Jersey, numerous fossil specimens were unearthed and happened to find their way into the hands of the early geologists and paleontologists who were beginning to describe and name the fossil faunas and floras of North America. Among these were such famous men as Joseph Leidy, E. D. Cope, and O. C. Marsh. The specimens they described and illustrated formed the basis for much of our subsequent knowledge about the paleontology of the Late Cretaceous and Early Tertiary in eastern North America.

The focus of the early workers was primarily descriptive and taxonomic, as they attempted to ascertain the systematic relationships of the new specimens forwarded to them from a variety of sources. Modern studies have been more integrated interpretations of paleoecology and biostratigraphy (Gallagher, 1991, 1992, 1993). With the increased interest in major geological boundary events such as mass extinctions, the section exposed at the Inversand Pit has assumed greater significance as a paleobiological record around one such datum, the K/T boundary. Although some previous workers have interpreted the stratigraphic relationship in the New Jersey K/T section as an angular unconformity (with the attendent implication of a large gap in the record of at least several million years) we have shown elsewhere (Gallagher, 1993; Gallagher, Parris and Spamer, 1986) that there is an alternative interpretation that does not require the supposition of an angular unconformity that is not measurable or observable in outcrop.

This interpretation involves the recognition of depositional rate change and condensation of the section along strike in a tectonically quiescent passive margin setting undergoing thermal and density subsidence during a period of sea level fluctuations. This produced a series of stratigraphic sequences marked at the base by glauconitic deposition and continuing upward into clays, silts and sands as the transgressive phase waned and the depositional regime changed. At the Inversand Pit, the contact between the Navesink and the overlying Hornerstown Formation is more accurately described as a disconformity or diastem (see Figure 1). It is quite smeared out by bioturbation, but there are no indications of a major unconformity such as gravel layers or indurated beds and no obvious differences in dip. What time is missing here is probably of an order of magnitude smaller than the kind of gap implied by an angular unconformity. Moreover, while the lithostratigraphic section is starved (and glauconitic sedimentation is interpreted as taking place at very low rates of deposition) and the sequence is condensed with respect to the thicker and more clastic sections to the northeast along strike, the biostratigrphic record is full and relatively less diluted by land-derived sediments. For the kinds of concentrations we see here we prefer to invoke Kidwell's (1989) model of complex condensed section hard-part beds, originally developed for the sequences exposed in the Miocene Calvert Cliffs section in Maryland. Kidwell sees these fossiliferous beds as representing something more than reworked layers. They incorporate a time-averaged taphocoenosis of organisms dying and leaving their remains to accumulate in sediment-starved settings over periods of tens of thousands to hundreds of thousands of years. The concentration of hard parts then results from the build up of skeletal remains undiluted by rapid large-volume deposition of sediment. Some remnants will be very worn-looking as a result of exposure on or near the sea floor for a protracted period of time. Biological modification of organic remains can be an important factor in altering the future fossils as they sit out on the sea floor, with all sorts of interactions affecting the hard parts including colonization by epibionts, microbial growth and subsequent grazing, scavenging, predation upon colonizers, sediment disturbance by bioturbators causing settling, boring, and handling by predators seeking prey hiding inside the remains (Gallagher et al., unpublished Sea Grant report, 1992).

Some preliminary precautions are required before descending into the pit. Firstly, the Inversand Pit is private property, and the Inversand Company does not permit casual unannounced visits; for legal reasons, a signed release form is necessary before entering the pit. Also the release form stipulates that any fossil specimens of scientific interest will be donated to the New Jersey State Museum, with appropriate credit given to the finder. These requirements are long-standing company policy, given the real dangers of working in the pit and the serious research value of the specimens from this last of the Jersey marl pits. For there is some risk in working in the pit; overzealous excavation of steep working faces may result in potentially lethal cliff-falls, and stepping on loose and unstable cliff-top edges may result in collapse beneath your feet. A less worrisome problem is entrapment in the "quick-mud" that forms in the wetter areas of the pit. The wet glauconite will assume a zero shear-strength consistency that will remind you of the mucky sea-bottom on which the fossil remains here were entombed; frequently a sistance is required to extricate unwary visitors from the wet greensand after they have sunken up to their knees in the sediment. For these reasons the Inversand Company prefers that recognized groups arrange for visits ahead of time through the New Jersey State Museum Bureau of Natural History.

Navesink Formation

At the base of the excavation here, the Navesink Formation of Maastrichtian age is exposed. The miners usually stop digging before hitting what is known as hardpan; this is the shellbed that is usually present in the lower part of the Navesink, consisting mostly of the oysters Exogyra and Pycnodont. Aside from the difficulty in digging up this more indurated layer, the carbonate of the shells is an undesirable contaminant of the desired product, greensand. So the exposure here is limited to the upper part of the Navesink; the basal shellbed can be seen nearby in the bed and banks of Chestnut Run near downtown Sewell. The top of the oyster concentration may be seen when pumping operations lower the water level of the pond at the bottom of the pit. Associated with this bed is a diverse Late Cretaceous fauna of marine invertebrates (for faunal lists see Gallagher and Parris, 1986, and Gallagher et al., 1986). Notable vertebrate discoveries from the top part of the Navesink Formation here include the two finest skulls of Mosasaurus maximus now known; one of these skulls is on display at the New Jersey State Museum in Trenton. Also of interest are the occasional dinosaur specimens found in the upper Navesink; Colbert (1948) reported on what is essentially the hindquarters of a duck-billed dinosaur, Hadrosaurus minor, excavated from near the formational boundary with the overlying Hornerstown, and other dinosaurdiscoveries include a hadrosaur femur found in the fifties, and a pathologic radius and ulna of a hadrosaur dug up in 1980. More recent finds include a couple of isolated hadrosaur vertebrae from around the contact, and a number of hollow dinosaur bones discoverd in 1990 that may pertain to the theropod Dryptosaurus. The type specimen of Dryptosaurus aquilunguis (Cope, 1866) was found close by, at the old West Jersey Marl Company pits in Barnsboro, in the upper part of the chocolate marl (the old marl diggers' term for the Navesink Formation). Additionally, large lignite logs and branches are sometimes discovered in the Navesink, reinforcing the impression of a nearshore marine depositional environment (for more detailed geochemical, stratigraphic and faunal data, see Gallagher 1992 and 1993).

Hornerstown Formation

The contact between the Navesink and the overlying Hornerstown Formation can be best described as paraconformable or disconformable. It is extensively burrowed, with burrows extending down into the Navesink Formation containing Hornerstown greensand. This is the primary unit of interest to the the Inversand Company; the Hornerstown Formation is a nearly pure (90% +) glauconite deposit that is mined here as a water-conditioner. The basal part of the formation (approximately the lower 3 decimeters) contains a very intriguing fossil fauna whose age has been the subject of debate for some time now. On the one hand, some workers (Minard et al., 1969: Owens and Sohl, 1969) viewed the basal Hornerstown as Danian in age, with fossils reworked as a result of erosion along an angular unconformity; other authors saw the basal Hornerstown assemblage as a latest Cretaceous fauna that biostratigraphically defined the top of the Cretaceous system (Olsson, 1963; Richards and Gallagher, 1974; Koch and Olsson, 1977) (see Figure 1). The early paleontologists seem to have missed the basal Hornerstown layer (see Weller, 1907, for example) and later workers gave a perfunctory faunal list (Minard et al., 1969). Systematic collecting efforts primarily by the New Jersey State Museum and the Academy of Natural Sciences have established a greater diversity for the Hornerstown basal assemblage and differentiated this assemblage from the fossil fauna found in the upper part of the formation here (see Gallagher and Parris, 1986, Gallagher et al., 1986, and Gallagher 1993 for more details). About two to three meters above the diverse but well-defined faunal horizon in the base of the formation, a much less diverse and more disseminated assemblage dominated by sponges, corals and brachiopods occurs in the darker upper part of the Hornerstown. This interval is characterized mineralogically by the occurence of radiating clusters of tiny acicular selenite crystals probably formed as a secondary mineral.

One of the principal arguments against a reworking explanation for the basal layer, known to State Museum workers as the Main Fossiliferous Layer (or MFL for short), is the taphonomy of the associated vertebrate remains. The MFL contains the last remains of the Cretaceous marine fauna, but the skeletal association of some of the vertebrate remains argues against transport of any sort. There is for example an articulated bird wing from the MFL. The complete remains of Beryciforme fish are present with scales in place; they are some of the most complete specimens of this type of fish now known. Complete turtles and partial articulated crocodilian skeletons round out the picture. Delicately sutured ammonite pieces are found in the MFL, as noted by Cobban and Kennedy (this volume). Mosasaur remains, Enchodus teeth, and Squalicorax teeth are othertypically Cretaceous forms found in the MFL. While some of this material appears worn or abraded, other specimens are quite fresh-looking. We prefer the model of a time-averaged assemblage sitting out on the sea bottom while glauconite deposition begins to accumulate very slowly. Elsewhere, I have estimated the time of accumulation for the MFL at about several hundred thousand years (Gallagher, 1993). I have suggested that this unusual concentration of organic remains represents the mass mortality at the end of the Cretaceous. An alternative view, which I first proposed in a GANJ meeting ten years ago (Gallagher, 1986) is that this layer may represent the mortality from the passage of an impact-generated tsunami wave, which could explain some of the features of this assemblage, such as the stacked oyster shells at the base of the MFL.

Vincentown Formation

Overlying the Hornerstown here are drab olive green deposits of the Vincentown Formation. The contact is not well exposed at present but can be marked by the presence of an indurated layer of limonite. Generally the Vincentown is characterized by a decrease in glauconite upward and a concomitant increase in quartz sand. It represents the regressive phase of the Hornerstown transgression. Fossils include rare encrusting bryozoa, solitary coral, and clusters of the calcareous tube-building clam Polorthus tibialis. The Vincentown is usually assigned a Thanetian age.

Kirkwood Formation

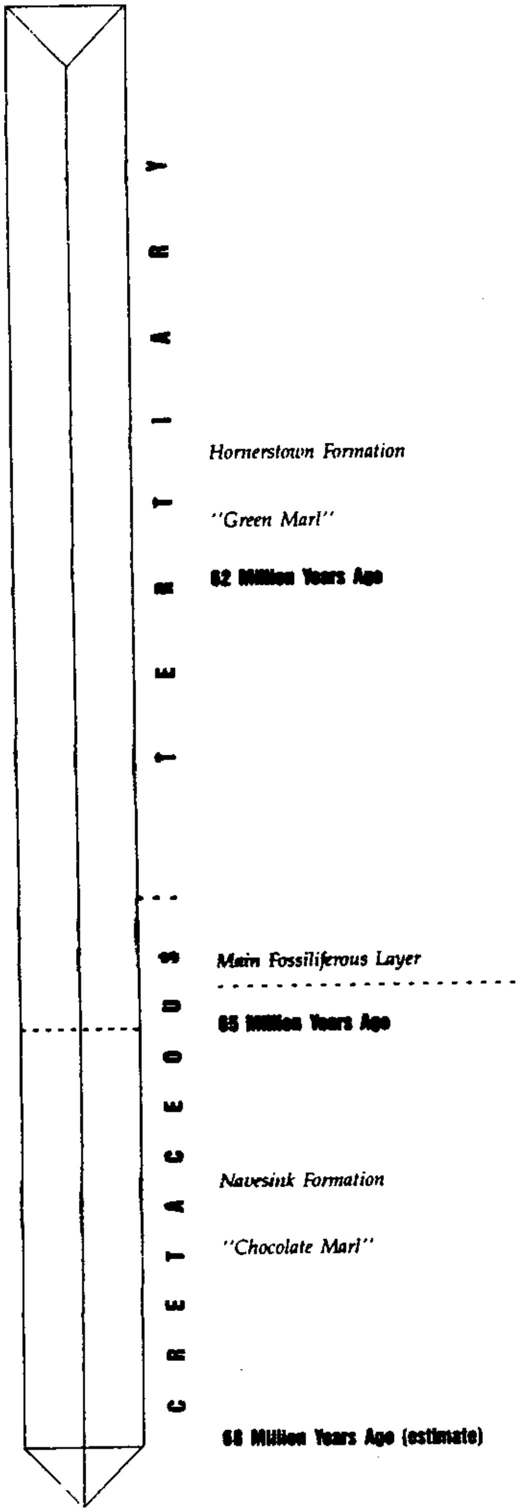
Overlying the Vincentown is the Grenloch Member of the Kirkwood Formation. The relationship between these formations is distinctly unconformable; the contact is an undulating surface that is often defined by an indurated layer of limonite. The Grenloch Member is a silty or clayey sand that is variegated in color. Although no macrofossils have been found right here in the pit exposure, nearby in Blackwood, Gibbsboro, and Washington Township the Grenloch Member has yielded petrified wood, occasionallly in the form of large petrified cypress logs. This suggests that the Grenloch Member is fluvial in origin. It is generally regarded as early mid-Miocene in age.

Pensauken Formation

Capping the section is the Pensauken Formation, a fluvial gravel deposit that has traditionally been assigned a Pleistocene age. It has been interpreted as an outwash gravel from glacial melt-back, but more recently (Newell et al., 1988) its age has been moved into the Pliocene. The only fossils in this unit at the Inversand Pit are the Paleozoic fauna (brachiopods, bryozoa, crinoid columnals, rugose and tabulate corals) found in the chert pebbles that were probably derived from Silurian and Devonian sources in the Appalachians (Howell and Hale, 1946).

Figure 1

STRATIGRAPHIC DIAGRAM
OF THE INVERSAND COMPANY MARL PIT AT SEWELL, GLOUCESTER COUNTY, NEW JERSEY



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